WALTER JOHN PARKS
Mapping Weed Ground Cover Using a Weed-activated Sprayer
(Under the direction of DAVID CURTIS BRIDGES)

Studies were conducted to develop a monitoring and weed mapping system for a weed-activated sprayer (WAS). Research developed a prototype that combined electronic logging of spray occurrences with location data from a global positioning system (GPS). The system was used to map and measure weed ground cover, and comparisons to random measurements obtained by traditional scouting and image analysis revealed that although random scouting provides precise, accurate ground cover estimates in small areas, they do not provide accurate estimations over the entire field. Studies were conducted to provide calibration techniques for the WAS, and models were developed to minimize overspray and underspray while maximizing leaf spray. To maximize performance, the WAS should be calibrated on the darkest and wettest area of the field. Weed populations were accurately mapped with a WAS. These maps can be used to make future weed control decisions.

INDEX WORDS: Site-specific weed management (SSWM), Weed-activated sprayer (WAS), Spatial Mapping, Precision farming, Prescription Farming, Weed control, Opto-electronic sensors, Reflectance, Spectrometer, Herbicide reduction, Pesticide reduction, Alternative pest management, Alternative farming, Integrated pest management (IPM), Herbicide sprayer,

MAPPING WEED GROUND COVER USING A WEED-ACTIVATED SPRAYER

by

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Luke 18:27

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INTRODUCTION

Since man planted his first seed, agriculture has been a precarious occupation with many possibilities for disaster including hail, drought, floods, wind, and pests. However, the most costly crop losses year after year are due to weeds. Since weeds have such a large economic impact it is imperative that they be controlled. Weed control can be mechanical, cultural, biological, or chemical. When used alone, biological and cultural control methods are often ineffective, and mechanical cultivation often leads to soil compaction and/or erosion. Chemical control is often the most effective method of weed control, but it can lead to herbicide resistance and is often associated with environmental concerns.

With the increasing prevalence of herbicide resistance and increasing production costs there is a need for herbicide management. Also, with the rise in public health and environmental concerns, there is political pressure to reduce pesticide use, despite the integral role they play in crop management. Since herbicides make up about two thirds of total pesticide use in the United States, reducing their use would significantly decrease overall pesticide use. There is a need for an environmentally sound, cost-effective, alternative weed management strategy.

Site-specific weed management (SSWM) could be the answer to herbicide use reduction. SSWM refers to the management of the in-field spatial variability of weed populations by directing control tactics to specifically target weeds using information gathered previously and/or at the time of control. Remote sensing, image analysis, Global Positioning Systems (GPS), Geographic Information Systems (GIS) and variable rate treatment (VRT), including optoelectronic sensors, can all be employed to manage spatially variable weed populations on a site-specific basis

There are many approaches to SSWM. One approach is temporally separate information collection and data processing and subsequent implementation of weed control procedures. This involves creating a map from visual inspections or image analysis and using these to predetermine spray decisions. These maps can be made, using a GIS, from data gathered with remote sensing techniques or from historical knowledge combined with location data gathered by GPS. Control measures are variably implemented across the field using the treatment maps with positions determined by GPS. Temporally separate weed control is a time consuming process, yet it allows for accurate herbicide treatment records. Alternatively, weeds can be detected real-time by image analyzing software or electronic sensors, which in turn can activate a spray mechanism. Automatic weed control makes instantaneous spray decisions, with very little human input, but accurate records are sometimes difficult to create.

Herbicide use reduction has been difficult to accomplish in the past without sacrificing control. With new technology, herbicides can now be selectively applied, while maintaining adequate control. This thesis details the use of a weed activated sprayer to map, control, and manage the spatial variability of weed populations. Studies were conducted to determine the sensitivity, proper operational speeds and equipment settings of the Patchen™ WeedSeeker sprayer, and an electronic monitoring device was developed to accurately record herbicide applications.

SECTION I.
LITERATURE REVIEW

Weeds In Agriculture

The so-called "Agricultural Revolution" started around 8000 BC. It was at this time that man planted seed and was able to form a civilization. Man no longer had to be nomadic. Instead, he could grow food in one place, and was able to establish permanent dwellings. It was also at this time that the first weeds probably came into existence. Weeds may have existed previously, or they could have developed characteristics that helped them survive in the new habitat created in man's new field. Weeds may have evolved from the crop plants man planted (Harlan and de Wet, 1965). Regardless, the plants were unwanted and the battle between farmer and weed began.

The term "weed" should be easy to define. However, one singular definition is not universally held in the field of weed science (Zimdahl, 1993). Weeds are similar to crop plants, which is why they often coexist with the crop in the habitat created when a field is cultivated. Weeds compete with crops for light, water, and nutrients. They also reduce crop quality and yield, and reduce harvest efficiency (Zimdahl, 1993).

Many definitions have been proposed over the years. Some of them convey a human perspective, such as a weed is a plant out of place or growing where it is not wanted (Blatchley, 1912). Or, a weed is a competitive, pernicious, and persistent plant that interferes with human activities, and as a result is undesirable (Ross and Lembi, 1985). Harlan (1975) suggested that although weeds are unwanted, this alone does not make them weeds. Along with the human component, a definition must recognize the biology and ecology of the plant (Bridges, 1995). Navas (1991) proposed a definition that includes all of the characteristics of a weed. He defined a weed as "a plant that forms populations that are able to enter habitats cultivated, markedly disturbed or occupied by man, and potentially depress or displace the resident plant populations which are deliberately cultivated or are of ecological and/or aesthetic interest."

Regardless of how a weed is defined, they do have a significant economic impact on agricultural production. Weeds account for about $4.1 billion in US crop losses every year. If not for herbicides, that figure would increase to about $19.6 billion annually (Bridges, 1992). This explains why herbicides account for a major portion of the total pesticides applied to crops. Chandler and Cooke (1992) reported that in cotton (*Gossypium hirsutum* L.) alone, yield reductions from weeds totaled $188 million annually across the U.S. Cotton Belt.

Weed Control

Attempting to kill, suppress, or otherwise control weeds dates back as far as agriculture does. Zimdahl (1993) gives a brief overview of the history of weed control. Man's first attempt to control weeds was probably mechanical control, such as hand pulling weeds and hoeing. He then probably started using pack animals and/or other humans to pull plows. These methods of control were used for thousands of years and are still used today. With the industrial revolution came machines. Because of the invention of the combustion engine, large plows could be used to cultivate the land. This was the most prevalent method of weed control during the 1950's. Forcella *et al*. (1993) stressed the idea that alternative weed control methods are available today such as biological, chemical, cultural, and physical. Biological and cultural controls have also been used throughout history, but by themselves they are not enough.

Lyon *et al*. (1996) suggested that herbicides have replaced tillage in many crop production practices. The term herbicide comes from the Latin *herba*, meaning plant, and *caedere*, meaning to kill. Herbicides have probably been used in one form or another since agriculture began. The ancient Greeks and Romans used table salt (NaCl) for weed control, and in the mid-nineteenth century sulfuric acid (H_2SO_4) was used. The first "modern" herbicide, 2,4-D (2,4-dichlorophenoxy acetic acid), was synthesized in 1941.

The introduction of modern herbicides has been one of the most crucial advances in production agriculture (Pike *et al*., 1991). Herbicides now lead in total acreage treated, total tonnage produced and total dollars spent of all pesticides, comprising 61% of all pesticide sales in 1992 (Bridges, 1992).

Herbicide Use Reduction

The use of herbicides is beneficial to agriculture, but their use also presents some problems. Current trends indicate that a reduction in herbicide use will be necessary in the coming years. Among these trends are the recent decline in the introduction of new herbicides, and the recent increase in herbicide cost. There is also a potential that some herbicides may be lost to herbicide resistance in weeds, and to re-registration problems. Finally, an increase in the ability to detect herbicides has given rise to public concern about herbicides in the food supply and the environment.

Herbicide Availability

Although there are many herbicides available today, they will not necessarily be available tomorrow. In 1956 about 1 out of every 2000 chemicals synthesized for possible pesticidal properties was registered. This rate declined to 1 out of every 18,000 by 1984. One reason for this is that the cost to develop a pesticide has risen dramatically from approximately $1.2 million in 1956 to $20 million by 1984 (Holt and LeBaron, 1990). Another reason is the difficulty in the pesticide registration process, which is represented in increased development cost. The few new herbicides that are introduced are usually registered for high margin crops, and at a much higher cost than older products (Lyons *et al*., 1996). This leads to a desire by farmers to reduce herbicide rates and help ease the strain from cost increases.

The difficulty in obtaining new herbicides is compounded by the fact that some existing products may not be reregistered. In 1988 Congress amended the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). This amendment required the re-

registration by 1997 of 611 active ingredients in about 44,000 products registered prior to November 1, 1984 (CAST Task Force, 1992).

Still another complication to herbicide availability is the dramatic increase in the incidence of herbicide resistance in the last 15 years (Holt and LeBaron, 1990). The 1998 International Survey of Herbicide-Resistant Weeds recorded 216 herbicide-resistant weed biotypes in 45 countries (Heap, 1999). When a weed biotype becomes resistant to a herbicide and then propagates, that particular herbicide becomes ineffective. One of the first cases of herbicide resistance was that of triazine resistance. The predominance of triazine-resistant weeds was largely due to the effectiveness and the widespread use of atrazine (6-chloro-N-ethyl-N'-(1-methyethyl)-1,3,5-triazine-2,4-diamine) for weed control in maize, and simazine (6-chloro-N,N'-diethyl-1,3,5-triazine-2,4-diamine) for weed control in orchards (Heap, 1999). This is a serious problem that threatens to further reduce the amount of available herbicides if proper herbicide management is not practiced.

Public Concern

An ever-decreasing percentage of the population is providing the required food and fiber for an ever-increasing population. This could not have been accomplished without the aid of pesticides, yet they are often blamed for contamination of the food supply and the environment (Hanks and Beck, 1998). In the past, herbicides were proclaimed modern miracles, but today many in society view them as environmental contaminants (Abernathy, 1992). One reason this trend has come about is because of ever-increasing analytical capabilities. Pesticides can now be detected in amounts as small as 0.01 part per billion (ppb) while 15 years ago the detection limit was less than 1 part per million (ppm) (Wauchope *et al*., 1994). This fact, and those mentioned previously, has lead to closer worldwide scrutiny of pesticides, regardless of whether the dangers are real or perceived. Canada (Brown and Steckler, 1995; Stonehouse, et. al., 1996), Denmark (Thonke, 1988, 1991), Sweden (Berson, 1988), and the Netherlands

(Ministry of Agriculture, 1990; Vernooy, 1994) have mandated that pesticide usage be reduced by fifty percent. Other countries have already, or are considering similar mandates for pesticide reduction (Hanks and Beck, 1998). In the United States today there are less than 2 million farmers while there are over 11 million members of various environmental groups (Abernathy, 1992). This imbalance of political influence could pressure legislators to further decrease the availability of pesticides in the United States.

Adding all of these factors together indicates that to maintain herbicides as a viable method of weed control, changes need to be made in the way herbicides are used. Control strategies that lead to more efficient herbicide use will be required to reduce overall pesticide usage.

Weed Spatial Variability

There are many different approaches to reducing herbicide use. Examples include using low-rate herbicide chemistries (Schweizer, 1988), biological control (Charudattan and Walker, 1982), cultural control (Zimdahl, 1993), improved formulations (Schweizer, 1988), and cover crops (Watson, 1992). This list is incomplete, but it shows there are many possible approaches to herbicide use reduction. However, none of these strategies, including traditional methods, take into account weed spatial distribution.

Weed distribution is defined as the position of weeds relative to each other (Wiles *et al*., 1992a). Distributions may be generally characterized in one of three ways, either regular, random, or patchy (also called clumped or aggregated) (Southwood, 1976, Radosevich and Holt, 1984). In a regular or uniform distribution, weeds are spaced an equal distance from each other. In such a case, weed density does not vary throughout the field. With a random distribution, every location in a field has an equal chance of being occupied by a weed. So, knowledge of the presence or absence of a weed at one spot yields no information about the likelihood of a weed at another spot. However, available data indicate that the distribution of weeds in commercial fields is generally patchy, and as such, most researchers feel that weeds are neither regularly nor randomly distributed (Hofsten, 1947; Marshall, 1988a, 1988b, 1989; Van Groenendael, 1988; Shropshire, 1989; Thorton *et al*., 1990; Navas, 1991; Thompson and Miller, 1991; Mortensen *et al*., 1992; Stafford and Miller, 1993; Donald, 1994; Rew *et al*., 1996; Zanin *et al*., 1998). A patchy distribution means that the presence of a weed at one site greatly increases the chance of a weed being close by. Weed density varies greatly across a field with a clumped distribution as opposed to one with a random distribution, which has very little variation.

Research has shown that weeds are not evenly distributed within a crop field. Marshall (1988a) found that in a wheat field, sterile brome (*Bromus sp.*), common couch (*Digitaria sp.*), and meadow brome (*Bromus commutatus* L.) grew in definite patches. Johnson *et al*., (1995) studied the spatial distribution of broadleaf and grass seedlings. They found that 30% of the sample areas were free of broadleaf weeds while 70% were free of grass weeds, indicating non-uniform distribution. Wiles *et al*. (1992b) studied the spatial distribution of broadleaf weeds in soybean (*Glycine max* L.) and found that approximately 90% of the seventy-nine species studied exhibited an aggregated distribution. Brown *et al*. (1990) also found that quackgrass (*Agropyron repens* L.) and dandelion (*Taraxacum officinale* L.) grew in well-defined patches. Research has also shown that weed patches tend to exist over time. In the United Kingdom, Wilson and Brain (1990; 1991) found that black-grass (*Alopecurus myosoroides* Huds.) grew in discrete patches over a ten-year period.

Since weeds grow in patches, they not only compete with the crop, but they also compete with each other, thus reducing their ability to negatively impact crop yields (Stoller *et al*., 1984). As a result, yield loss decreases as weed patchiness increases (Auld and Tisdell, 1988; Dent *et al*., 1989; Hughes, 1989; Brain and Cousens, 1990; Thorten *et al*., 1990). This phenomenon often leads to overestimation of herbicide requirements (Hughes, 1989; Thorten *et al*., 1990).

Weed Management Strategies

Growers, land managers, and consultants have long recognized the spatial heterogeneity in fields, yet resources, including herbicides, are applied to whole fields (Mortensen *et al*., 1998). Most weed-control strategies can be categorized as either a "control at any price" strategy or an "economic threshold" strategy (Hurle, 1998). These can be summarized in that in the former all weeds are sprayed regardless of density or distribution, while in the latter weeds are only controlled if the net economic gain in yield exceeds the cost of the control method. The economic threshold strategy uses decision models to determine the yield loss by assuming a regular or random distribution (Wiles *et al*., 1992a). In contrast, actual crop loss from weed competition depends not only on the density of weed populations, but also their composition and spatial distribution (Cousens *et al*., 1984).

In order to determine weed densities, an individual must survey the weeds in a field (Mumford and Norton, 1987). The scout estimates the average densities of weed species present, and this information is used to make post-emergence control decisions (Wiles *et al*., 1993). Randomly counting weeds is time consuming (Wiles, *et al*, 1993), and the aggregated nature of weed populations can hinder accurate estimations of weed densities (Marshall, 1988b; Wiles *et al.*, 1993). Still, there is potential for incorporating information about spatial distribution when using economic thresholds. Most of the time this is not implemented in the control at any price strategy, which has a threshold of zero, and where spatial distribution rarely plays a part in the decision process. Managing weed spatial distribution in an economic threshold strategy can allow weed control on a site-specific basis. This strategy of management leads to the area of research in weed science known as site-specific weed management (SSWM).

Managing Weed Spatial Variability

Site-specific weed management (SSWM) could lead to less herbicide use. SSWM refers to the management of the in-field spatial variability of weed populations by directing control tactics to specifically target weeds using information gathered previously and/or at the time of control. It can be argued that SSWM is simply a grower hand pulling weeds or spot spraying a particular area in his field. While these methods do site-specifically control individual weeds, they do not take into account the entire weed population. Also, a farmer could operate his equipment in reaction to spatial variability such as manually turning the spray boom on or off. However, it is often difficult for humans to accurately perform such tasks, and operators who don't have financial stock in the operation have no motivation to do so (Schueller and Wang, 1994). Only recently has technology become available to implement SSWM. There are many approaches to SSWM, but they all implement one or more of the modern day technologies of Global Positioning System (GPS), geographic information systems (GIS), variable rate treatment (VRT) and/or remote sensing.

GPS and GIS in SSWM

Since the dawn of time man has struggled with navigation. He probably began by navigating by the stars, and when compasses were invented he was able to navigate even more accurately. Still this wasn’t accurate enough. In modern times, with the ability to travel by boat and then by airplane, the world got seemingly smaller, yet man could navigate no better than his ancient predecessor. The United States military needed a way to coordinate troop movements any where in the world so they developed a navigation and positioning system, through the use of satellite and computer technology, called Global Positioning System (GPS) (Hurn, 1989).

Being able to determine the location of any field operation or data collection point is important in SSWM (Webster and Cardina, 1997). Global positioning system (GPS) is a convenient technology for locating positions. It allows users to determine three-dimensional position anywhere in the world with a fairly high degree of accuracy (Tyler, 1992). GPS determines position by pseudo-range positioning based on the time delay between the signals leaving from at least four satellites and reaching the receiver. This method is often called triangulation, which infers a triangular pattern and raises the question for the necessity of the fourth satellite. The reason for four satellites is that three are used for position and the fourth is used for resolution of the clock offset. Although four are required, six or more are needed for accurate measurements (Hurn, 1989). Errors due to atmospheric delays, multipath error (multiple receptions from source and reflections off water, structures, etc.), orbit deviations, etc. yield an accuracy of about 100 meters (Hurn, 1993). Precision applications require more accuracy than this, so to adjust for this error, a GPS unit must be coupled with another receiver that provides correction information. This is known as differentially corrected GPS, or DGPS. These units make the readings accurate to within one meter or less (Hurn, 1993).

Knowing the exact location of weeds in a field is of little value if there is no way to keep a record of that location and the information associated with it. Usery *et al*. (1995) researched the appropriateness of using a geographic information system (GIS) to link positions determined by DGPS in precision management. They concluded that placing a GIS at the center of the process would offer great advantages as the use of the technologies expand in both agricultural research and production. The definition of GIS has been heavily debated (Maguire, 1991), but Burroughs (1991) proposed the definition most consistent with site-specific weed management. He defined GIS as "a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world." Using a GIS allows for the incorporation of DGPS, VRT, remote sensing, and general knowledge about historical weed populations into SSWM. One problem arising when using a GIS is that often all the data is not collected at the same resolution. This leads to difficulties in geographically comparing the data. This problem can be avoided if proper care is taken when recording points (Green, 1997).

VRT in SSWM

In traditional cropping systems pesticides are applied as "broadcast" applications. Giles and Slaughter (1997) described broadcast spraying as the process of spraying the entire field "using a linear array of nozzles discharging individual overlapping patterns which combine to produce a single, uniform, continuous spray pattern." Rutherford (1985) described the wastefulness of broadcast pesticide application as "the least efficient industrial process on earth." These applications are wasteful because they do not take into account the location of the target plant, only the location of the crop plants, which are fixed and not variable. This approach often leads to overapplication of pesticides. Sometimes it leads to under application.

Variable rate treatment (VRT), in contrast to broadcast treatment, is the application of materials such as pesticides, nutrients, or water to a specific small area of a field (Lu *et al*., 1997). The goal of VRT in SSWM is to reduce inputs while maintaining adequate control. VRT can be accomplished according to two very different approaches: Automatic Control or Temporally Separate Control (Schueller, 1992). Automatic (real-time) Control is where one or more sensors, located on the application machinery, control the application (Schueller and Wang, 1994). Control decisions are made instantaneously as the machinery moves across the field. In Temporally Separate (predetermined) Control, the control of the applicator is completely uncoupled from the sensors (Schueller and Wang, 1994). The manager makes control decisions from data gathered by one of several means and a control map is produced. This map is then used to direct control tactics.

Remote Sensing

Having a record of the location of weed patches, being able to navigate back to that location, and varying control methods at that location are only part of SSWM. A projected scenario for the future is a farmer viewing his field on a video screen to determine the condition of his crop (Jackson, 1983). If these images are able to provide sufficient warning of upcoming problems, they can be used to take preventative actions, including controlling weed populations (Hatfield and Pinter, 1993). New technologies such as remote sensing are being implemented in agriculture today. Remote sensing is the act of detection and/or identification of an object, series of objects, area, or phenomenon through the analysis of data acquired by a device that is not in contact with it (Lillesand and Kiefer, 1996). Non-agricultural applications for remote sensing range from studying temperature variations to geologic mapping, while sensing techniques range from radar scanning to satellite imaging (Crum, 1997). Agricultural applications of remote sensing techniques include identifying crops and/or weeds, predicting yields, and detecting crop stress and diseases (Hahn and Muir, 1994). Two techniques can be used for detecting weeds with remote sensing. The first is to detect some geometric difference between the weed and soil (and/or the crop), known as machine vision, and the second is to discriminate between them by spectral reflectivity differences (Shearer and Jones, 1991; Thompson *et al*., 1991). Zwiggelaar (1998) defines the former as imaging and the latter as non-imaging devices.

Machine Vision (Imaging)

Identification of weeds by image analysis is known as machine vision. Machine vision generally uses shape or position features to identify weeds, but plant color characteristics can be integrated as well. The theory of operation includes photographing and digitizing the image and then classifying the image by parameters such as color, roundness, thickness, elongatedness, and aspect (Cardenas-Weber *et al*., 1988; Guyer *et al.*, 1986; 1993; Woebbecke *et al*., 1992; 1995a; 1995b).

Woebbecke *et al*. (1995b) used binary images to discriminate between plants that had different shapes. Since some monocots have different morphological architectures than dicots, analysis of the geometry of the canopy should allow for species differentiation. Criteria included overall shape, roundness, aspect (the ratio of the x and y length of the canopy), perimeter/thickness (describes plant shape), elongatedness (ratio of area to thickness squared), and first invariant central moment (ICM_1) (density of leaves around the crown of the canopy). They found that the shape features, aspect, and ICM_1 distinguished plants best.

Woebbecke *et al*. (1995a) conducted a similar experiment, but used different color indices, red (r), green (g), and blue (b), to distinguish plants from a background matrix. The indices they tested included r-g, g-b, (g-b) / |r-g|, and 2g-r-b. They found that the modified hue 2g-r-b index and the green chromatic coordinate worked best, although the modified hue was the most computationally intensive. Guyer *et al.* (1986) conducted a similar study, but measured ratios of near infrared to visible wavelengths. They were able to distinguish plants from the background soil matrix based on the reflectance properties of plants and soil.

Reflectance Properties

Weed detection by optoelectronic devices relies not on differences in shapes and spectral reflectance, but on differences in reflectance alone. There are three possible fates for light when a plant intercepts it: reflectance, absorptance, and transmittance (Hatfield and Pinter, 1993). However, reflectance in distinct areas of the electromagnetic spectrum is the most commonly employed by remote sensing techniques. The theory of operation of optoelectronic sensors involves detecting weeds by measuring reflectance differences either between weeds and crops, or between weeds and soil.

To date there are no commercially available sensors that can distinguish two different species from one another based on reflectance differences. Zwiggelaar (1998) reviewed in depth the potential for using plant spectral properties in crop/weed discrimination. He concluded that because of temporal variations, a plant's reflectance characteristics alone are not enough to distinguish between crops and weeds. However, if a combination of reflectance and spatial geometrical properties were used, species differentiation is possible (Zwiggelaar, 1998). This method has thus far been only partially implemented in research (Guyer *et al*., 1984, 1986, 1993; Cardenas-Weber *et al*., 1988; Han and Hayes, 1988; Blazquez, 1990; Woebbecke *et al*., 1992).

In contrast to interspecies differentiation, distinguishing weeds from the background soil matrix has been accomplished (Haggar *et al*., 1983; Felton, 1990; Felton *et al*., 1991; Nitsch *et al*., 1991; Shearer and Jones, 1991; Hanks and Beck, 1998; Wicks *et al*., 1998). The theory of operation is that in the photosynthetically active region (400 to 700 nm), plants have relatively low reflectance compared to soil, while in the near-infrared (NIR) region (700 to 1000 nm) plants have a significantly higher reflectance than soil (Jones, 1996). Optoelectronic devices take advantage of this difference in reflectance characteristics, allowing spray system control based on the presence or absence of a weed.

Physical and chemical properties of plants and spectral properties of the emission source determine the reflectance characteristics of plants (Myneni and Ross, 1991). The emission source is usually the sun, but it can be an artificial source, such as the one used in the Patchen™ WeedSeeker (Hanks and Beck, 1998). Reflectance characteristics are also determined by the background matrix (i.e. soil) (Hoffer, 1978; Bauer, 1985). Soil reflectance is dependent on surface moisture, organic matter content, and soil particle size (Bowers and Hanks, 1964). Dry soils are more reflective than wet soils in the 320 to 1000 nm range (Cirpra *et al*., 1971; Condit, 1971). The visually apparent darkening of soil when it gets wet explains the reduced reflectance in the visible spectrum (Planet, 1970). Stoner *et al*. (1980) pointed out that although similarly colored soils may exhibit similar reflectance characteristics in the visible spectrum, there are often significant differences in the near and middle infrared region of the spectrum. So, weed sensors that are activated by reflectance differences between soil and plants, must take into account both the visible and the non-visible near infrared regions of the spectrum.

Temporally Separate Control

As mentioned previously, in temporally separate control weed locations are determined at one time and control measures are implemented at a different time. This type of control is based on creating weed maps to use in controlling the patchy weed populations. Maps can be based on visual observations, machine vision, or aerial photography, (which implement spectral reflectance differences). Once maps are created, control is accomplished using various applications techniques, but most include position references using GPS, control rates stored in a GIS, and variable rate controllers. Temporally separate control not only has advantages over real-time control, but it also has some disadvantages as well. Presently there has been no research using machine vision to create weed maps, only those mentioned earlier that show the possibilities.

Visual Weed Maps

The knowledge that farmers gain when surveying fields could be important in developing weed maps (Stafford and Miller, 1993). However, this method of detection gives only a weed count while forsaking navigable location coordinates for control maps. Stafford *et al*. (1996), Rew *et al*. (1996), Green (1997), and Lass and Callihan (1993) used GPS to determine locations of visually identified weeds.

Stafford *et al*. (1996) developed a system of hand mapping weed populations by using a hand-held datalogger. They used a palmtop personal computer (PC) combined with a DGPS to enter weed and location information simultaneously as the operator walked through the field and outlined weed patches. Rew *et al*. (1996) conducted an experiment in which two operators rode on a vehicle and visually estimated weed densities along a tramline. The operators entered weed density data into a laptop PC, which was combined with location data provided by a wheel sensor that measured the distanced traveled along each tramline. Green (1997) also conducted a study in which they mapped weed patches using a laptop computer with a DGPS mounted on an all-terrain vehicle (ATV). Patches of weeds were mapped by driving the ATV around them. Tredaway *et al*. (1998) mapped common cocklebur (*Xanthium strumarium* L.), trumpetcreeper (*Campsis radicans* (L.) Seemann), broadleaf signalgrass (*Brachiaria platyphylla* (Griesbach) Nash), and johnsongrass (*Sorghum halepense* (L.) Persoon) in a corn (*Zea mays* L.) field. The field was divided into plots and weed measurements were made in each one. No GPS was used. Lass and Callihan (1993) mapped weed infestation boundaries with GPS and combined location information with other known physical features such as roads and lakes in a GIS.

Remotely Sensed Maps

A few studies have been conducted to create weed control maps by using aerial photography to distinguish weeds from crop canopies. Menges *et al*. (1985) conducted a study in which they looked at the species differentiation among several weed crop combinations. They used a field spectroradiometer to determine the reflectance characteristics of various plants. Then they photographed fields at altitudes of 610 to 3050 m with color infrared film. Armed with the knowledge of reflectance differences, they were able to distinguish climbing milkweed (*Sarcostemma cyanchoides*) in orange (*Citrus sinensis*); ragweed parthenium (*Parthenium hysterophorus*) in carrot (*Daucus carota* L.); johnsongrass in cotton and grain sorghum (*Sorghum bicolor*); London rocket (*Sisymbrium irio*) in cabbage; and palmer amaranth (*Amaranthus palmeri* Watson.) in cotton. Richardson et al. (1985) and Everitt and Deloach (1990) conducted similar studies. Everitt et al. (1987) were able to distinguish broom snakeweed (*Guitierrezia sarothrae*) and spiny aster (*Aster spinosus*) among other rangeland plant species. The objective in all these studies was to estimate the infestation of weeds and to determine the possibility of detection with aerial photography. Detection was possible because they took the photographs late in the season when crops and weeds had different morphologies (e.g. flowers were present or foliage absent). This is much too late for weed control purposes. Also, none of these studies created control maps or determined herbicide savings when spatial distribution was a factor in herbicide application.

Variable Rate Treatment With Maps

Brown and Steckler (1995) created a prescription map from remotely sensed data and determined possible spray savings. They were able to distinguish green foxtail (*Setaria viridis*), common lamb's quarters (*Chenopodium album* L.), dandelion, and quackgrass from no-till corn. They ran the weed combinations through a decision model and created a control map with various herbicide rates. They predicted a potential herbicide saving of forty percent. Green (1997) and Tredaway *et al*. (1998) took this concept one step further. As mentioned earlier, Green (1997) mapped patches of Florida beggarweed (*Desmodium tortuosum*) in an 18 ha peanut (*Arachis hypogea*) field with an ATV. Herbicide prescription maps were made, and herbicide was applied using a variable rate sprayer according to the map requirements. Tredaway *et al*. (1998) made weed measurements in separate blocks, and determined what rate of preemergence (PRE) herbicide to apply the next season. They applied variable rates across the field, and then followed up with variable postemergence (POST) treatments as needed.

There are some advantages and constraints on using selective spraying with weed maps. Paice *et al*. (1995) suggested that spatial accuracy in SSWM is not only limited by the resolution of navigation and mapping systems, but is also limited by the delay in activation of solenoid valves. Webster and Cardina (1997) studied the accuracy of using GPS for visual and remote sensing weed mapping. They wanted to determine the precision of GPS in measuring the area of weed patches and navigating back to these positions. They found that patch size was inversely proportional to navigational error in that as the patch size increased, percent error decreased. While they were able to navigate to within 1.58 m of the correct quadrant, 73% of the time they had submeter accuracy. So using GPS for weed mapping does not allow for very small patch treatment (i.e. $< 2\ m^2$), but in most field situations this accuracy is sufficient. Another advantage of map-based systems is it reduces operation time and compaction potential because the tractor travels only over weed-infested portions of the field (Thompson *et al*, 1991). This argument holds true in some cases, but an operator will most likely travel over the entire field letting the sprayer turn on and off at will. Also, it takes a considerable amount of time to identify weed populations and create a weed map.

Real-time Control

Automatic (real-time) weed control is accomplished through the use of optoelectronics that detect the presence of plant material and then activate a solenoid to apply herbicide. The sensors may either employ their own light source or use ambient light.

Weed Activated Sprayers Using Ambient Light

Haggar *et al*. (1983) developed a prototype, hand-held intermittent sprayer that used ambient light. They developed a sensor that measured the (Red + NIR)/ NIR ratio, which when the correct ratio was achieved it activated an Oxford Precision Sprayer. Results showed the sensor proved effective in distinguishing plants from soil, but there was a delay in the activation of the solenoid. As a result some weeds were missed at the beginning of the weed patch while there was over spray at the end of the weed patch. Haggar *et al*. (1983) felt these problems could be corrected with repositioning of the sensor and changing the aspect to the direction of travel.

Felton *et al* (1991) developed another weed activated sprayer (WAS) prototype. It used optical fibers to transmit reflected energy from the sensor field of view (FOV) through red and NIR filters to an analog-to-digital (A/D) converter. Digital data were transmitted from the A/D converter to a central processing unit (CPU), which made a logical decision as to whether or not green vegetation had been seen. If the answer was positive the CPU in turn activated a solenoid. The prototype was adapted to an 18-meter spray boom and was tested on 33 farms in Australia for a total of 2,681 hectares. Compared to broadcast application they realized an average of 90% spray saving. Later marketed as Detectspray, this WAS has been further studied by Ahrens (1994), Blackshaw *et al*. (1998a; 1998b), and Wicks *et al*. (1998) among others. Blackshaw *et al*. (1998b) studied the factors that affected the operation of the Detectspray. They found that the minimum weed size the system can detect varied with plant species. Broadleaf species required three to four leaves to be consistently detected while grass species required five to six leaves, and smaller weeds were only detected at high densities. Blackshaw *et al*. (1998b) also concluded that operators should only use the sprayer in full sunlight since ambient light levels greatly affected sprayer performance. Wicks *et al*. (1998) compared three different application techniques: traditional broadcast, Detectspray alone, and a "dual boom" system. The dual boom system combined a reduced rate broadcast application and a WAS to apply a higher dose for spot treatment. Larger weeds were sprayed twice, but small weeds undetectable by the sprayer were sprayed only once. Results indicated that the dual boom system gave 4.5 times better weed control than the WAS alone.

The Detectspray is difficult to use in row crop agriculture for several reasons. First, it was developed for noncrop situations (Hanks and Beck, 1998). Secondly, the plant sensor has a variable field of view (FOV) at different heights (Hanks and Beck, 1998). Small weeds often go undetected (Hanks and Beck, 1998; Wicks *et al*., 1998). Use is limited to adequate sunlight because it uses ambient light (Blackshaw *et al*., 1998b). Finally, the distance between sensor and nozzle has to be changed according to speed (Hanks and Beck, 1998).

Weed Activated Sprayers Possessing Own Light Source

Bowman Manufacturing Company (Bowman Manufacturing Co.; Lubbock. Texas) designed another type of weed-activated sprayer that uses infrared light beams. The sensor is much simpler in operation than other WAS. An infrared light beam is emitted on one side of the sensor, which completes a circuit as long as it is received by the detector on the other side. The spray boom is set at a certain height above the crop canopy, so when the beam encounters a tall weed, the circuit is broken triggering a solenoid that releases a timed amount of herbicide. This is the same type of technology used in department stores to let shop owners know when a customer has entered the store. Green (1997) assessed the efficiency of the Bowman sprayer, and found that although it worked well in sensing tall weeds, it missed those below the crop canopy. Another drawback to the sprayer is that by the time weeds are tall enough to be detected, they are much more difficult to control.

Shearer and Jones (1991) developed a prototype weed-activated sprayer that used a near infrared LED (900 nm with a 100 nm bandwidth) and a phototransistor receiver to distinguish weeds from the soil, thus not relying on ambient light conditions. Logic circuits were developed to account for the delay time from sensing to spraying. These circuits in turn activated a solenoid valve to dispense herbicide when weeds were detected. Using fiber optics to transmit to and receive light from the sensor afforded protection for sensitive components, since these could be placed away from the ground. Shearer and Jones (1991) found that the while the prototype sprayer was as effective as broadcast applications in control, ground speed was a severely limiting factor.

More recently was the development of the Patchen™ WeedSeeker. Like the Detectspray and the sprayer developed by Shearer and Jones (1991), the WeedSeeker determines the presence of weeds based on reflectance differences between soil and plants. Unique characteristics of the WeedSeeker, however, are the use of its own internal light source and a constant field of view (FOV) for heights of 40 to 80 cm above the soil (Hanks and Beck, 1998). The WeedSeeker uses two different types of light emitting diodes (LED) to illuminate plants and soil in its FOV. One LED emits light at 660 nm with a 20 nm bandwidth providing red light, while the other LED emits light at 770 nm with a 30 nm bandwidth to provide NIR light (Personal communication with Patchen Inc.). Each sensor projects a 0.5-cm wide beam across its FOV. A microcomputer inside the module controls the LED's and has software stored on an Erasable Programmable Read Only Memory (EPROM) that processes and makes decisions about the signals received from the sensors FOV. If a weed is detected a solenoid is activated which releases a small amount of chemical (Hanks and Beck, 1998). Because the WAS cannot distinguish between the crop and weeds, sensors should be placed in a hood to allow inter-row application of nonselective herbicides (Hanks and Beck, 1998).

Economics of SSWM

With all the previously mentioned research, where maps were created or weeds were actually treated, some degree of herbicide savings was realized. With temporally separate control maps Rew *et al* (1996) predicted 69-78 % reduction in herbicide, Brown and Steckler (1995) predicted a 40% in herbicide, while Green (1997) had a 70% reduction in herbicide. With real time control the Bowman height-selective sprayer had 61% to 86% reduction in herbicide (Green, 1997), the Detectspray provided 90% (Felton *et al*, 1991), 13% to 87% (Ahrens, 1994), 50% to 80% (Blackshaw *et al*, 1998a), and a 1% to 92% reduction (Hanson and Wicks, 1992), while the Patchen™ WeedSeeker provided 63% to 85% reduction in herbicide use (Hanks and Beck, 1998).

It is obvious that there is a large amount of variability in herbicide reduction within and between the different approaches. The reason for this is the differences in the densities and distribution of the weed populations. Oriade *et al* (1996) stated that the degree of patchiness is the most important factor in SSWM. Haggar *et al*. (1983) stated that herbicide savings were directly related to the area of the weed patch. In other words, the more distance there is between weed patches the more herbicide savings that can be realized. If most of the field is infested with weeds, then herbicide savings will be close to zero.

For SSWM to be implemented in production agriculture, not only the amount of herbicides must be reduced, but also input costs will have to be reduced enough to offset the cost of application. It may appear that in the research conducted thus far most of the approaches resulted in cost savings. What also has to be considered are the cost of the equipment, the amount of time spent creating treatment maps, and the cost of the herbicide used.

Conclusions

It is apparent that there is an impetus to reduce the amount of herbicides and other pesticides that are used in agriculture. Taking into account the spatial variability of weed populations and prescribing treatment options to control them is a very inviting alternative to broadcast applications and could result in a significant herbicide use reduction. Site-specific weed management is a very new area of research in weed science, and information is lacking about which is the best approach. Yet, the data available suggest that real-time weed detection could be the most useful, successful, and practical approach to SSWM. Regardless of the application approach taken, SSWM has the potential to both reduce input costs and the amount of pesticides entering the environment.

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SECTION II.

DEVELOPMENT OF AN ELECTRONIC MONITORING SYSTEM FOR A WEED-ACTIVATED SPRAYER[1]

[1]W.J. Parks, D.C. Bridges. To be submitted to *Computers and Electronics in Agriculture*

ABSTRACT

A system was developed to monitor the activity of a weed-activated, herbicide sprayer, and to combine location coordinates with these spray measurements in order to map weed populations in an agricultural field. The system was designed around a data logging system that used a data logger to record spray instances, and a global positioning system to provide location information. Several prototypes were developed, and studies were conducted to evaluate the precision and accuracy of each prototype. Prototype 1, based on flow sensors, operated reliably, but lacked the ability to record spray instances for each weed sensor. Prototype 2, based on logging the duty cycle from switch closure modules, was able to record spray occurrences for each sensor, but due to grounding problems did not operate reliably. A final prototype incorporated optical isolators to electrically isolate the logging side from the sensing side. Prototype 3 was found to accurately sense and record spray instances, and this information was combined with position coordinates to create weed ground cover maps. The monitoring system has the potential to be used to accurately determine weed ground cover in a more efficient, thorough, and rapid manner than traditional field scouting. The information that is gathered with this system could be useful in predicting yield loss from weeds and for making future weed control decisions.

INTRODUCTION

Although herbicides play an important role in production agriculture, current trends suggest that a reduction in herbicide use will be necessary in the next millenium. Among these are decreasing herbicide availability (Holt and LeBaron, 1990), increasing public concern about pesticides (Abernathy, 1992), and increasing crop production costs. There is a need for an environmentally sound, cost-effective, alternative weed management strategy. Site-specific weed management (SSWM) could be the answer to herbicide use reduction and lowering input costs. SSWM refers to the management of the in-field spatial variability of weed populations by directing control tactics to specifically target weeds using information gathered previously and/or at the time of control (Parks, 2000).

Conventional herbicide application is made as a broadcast treatment of a single rate over the entire field, and control decisions based on weed density alone can result in over-application of herbicide (Hughes, 1989; Thorten *et al*., 1990). Rutherford (1985) described the wastefulness of broadcast pesticide application as "the least efficient industrial process on earth." Broadcast spraying also does not provide any record of where weeds are located and their densities at these locations. However, it is useful to know weed population locations. Most scientists feel that weeds generally grow in distinct patches (Hofsten, 1947; Marshall, 1988; Thorton *et al*., 1990; Navas, 1991; Thompson *et al*., 1991; Mortensen *et al*., 1992; Stafford and Miller, 1993; Donald, 1994; Rew *et al*., 1996). Growers, land managers, and consultants have long recognized the spatial heterogeneity in production fields, yet herbicides have been applied to whole fields despite this recognition (Mortensen *et al*., 1998).

Spraying only where the weeds are present could result in significant herbicide use reduction (Ahrens, 1994; Audsley, 1993; Rew *et al*., 1996; Green, 1997). Various technologies have been implemented in developing weed-activated sprayers (WAS) (Haggar *et al*., 1983; Felton *et al*., 1991; Shearer and Jones, 1991; Green, 1997; Hanks and Beck, 1998). These are sprayers that apply herbicide in response to the presence of a weed. One such weed-activated sprayer is the Patchen™ WeedSeeker (Patchen™ Inc., Mayfield Equipment Co.; Ukiah, California). The WeedSeeker determines the presence of weeds based on reflectance differences between soil and plants.

Unique characteristics of the WeedSeeker are the use of its own internal light source and a constant field of view (FOV) for heights of 40 to 80 cm above the soil (Hanks and Beck, 1998). The WeedSeeker uses two different types of light emitting diodes (LED) to illuminate plants and soil in its FOV. One LED emits light at 660 nm with a 20 nm bandwidth providing red light, while the other LED emits light at 770 nm with a 30 nm bandwidth to provide NIR light (Personal communication with Patchen Inc.). The theory of operation of the Patchen™ system is that in the photosynthetically active region (400 to 700 nm), plants have relatively low reflectance compared to soil, while in the near-infrared (NIR) region (700 to 1000 nm) plants have a significantly higher reflectance than soil (Jones, 1996). The optoelectronic sensors in the Patchen™ system take advantage of this difference in reflectance characteristics, allowing spray system control based on the presence or absence of a weed. Each sensor projects a 0.5-cm wide beam across its FOV. A microcomputer inside the module controls the LED's and has software stored on an Erasable Programmable Read Only Memory (EPROM) that processes and makes decisions about the signals received from the sensors FOV. If a weed is detected a solenoid is activated which releases a small amount of chemical (Hanks and Beck, 1998). Because the Patchen™ system cannot distinguish between the crop and weeds, sensors should be placed in a hood to allow inter-row application of nonselective herbicides (Hanks and Beck, 1998).

The WeedSeeker can accurately spray weeds that it encounters (Hanks and Beck, 1998), but as in conventional broadcast spraying there is no record of where the weeds were located. The WeedSeeker simply reacts to weed presence, but it doesn't possess the electronic capability to record the quantity and location of spray occurrences. Nor is there any built-in system monitoring equipment for the operator to know if the system is operating correctly. The objectives of this study were to develop and evaluate a potential electronic monitoring system in order to be able to use the Patchen™ WeedSeeker to map weed ground cover and possibly be able to monitor system activity.

PROTOTYPE I

The first prototype was developed with the idea of using flow rate sensors to measure spray instances. This was chosen to provide a low cost, simple to install and maintain spray detection method. Flow sensors (Midwest Technology Inc., Springfield, Illinois) were mounted on the connection hose leading from the spray pump to the manifold of each hood. This configuration allowed a total of only three sensors for nine WeedSeeker sensors. A 12-volt DC battery provided current to the flow sensors where an internal switch sent the voltage to the monitoring system when liquid passed through the flow sensors. The monitoring system consisted of three, two-way, normally open relay switches, which closed a circuit when charged by the voltage from the flow sensors. The circuit consisted of four, 1.5 volt D-cell batteries connected through the relays to a Campbell CR10 datalogger (Campbell Scientific, Inc., North Logan, Utah). The datalogger was set to collect a voltage measurement every 0.5 seconds, but it was only capable of outputting a measurement every 2 seconds. A differentially corrected global positioning system (DGPS), an Omnistar 7000 DGPS (Omnistar, J.E. Chance and Assoc.; Houston, Texas) receiver was used to determine coordinate locations of individual spray occurrences. Clock times on the CR10 and GPS were synchronized in order to compare location data with measurement data. All of the electronics were mounted into a custom-built box mounted on the sprayer. A seat was attached to the sprayer to allow an individual to ride the equipment and monitor system activity.

An experiment was conducted to test the reliability of the monitoring system. Each hood was calibrated to apply 60 L/ha over the 0.7-m-wide area covered by each hood at a speed of 4.828 km/h. Three WeedSeeker Model PhD 612 sensors independently controlled three TJ6205 flat fan nozzles in each hood. Operating pressure for the sprayer was 138 kPa, provided by a 12 V diaphragm pump, and liquid was sprayed out of a three-L bottle. Water with a spray dye was used as a visual indicator of vegetation that was sensed and sprayed. The system was charged to fill all plumbing and each run began with a known volume. Remaining volume was recorded for each spray pass to compare with the volume predicted by the monitoring system. An individual rode on the equipment and monitored the logging system.

Visual evaluation of spray dye location showed the Patchen™ did react appropriately to weed presence and applied a dose of liquid to them, as was reported by Hanks and Beck (1998). The volume and WAS measurements collected with Prototype I appeared to be closely related to each other (Figure 1). Results indicated that error in predicted volumes from the monitoring system differed an average of 64.3 ml across all transects, and error ranged from 0.4% to 22.9% with an average error of 7.8% (Table 1). Statistical evaluation revealed a fairly high correlation in that the regression equation had a slope of 0.76 and an R^2 of 0.79 (Figure 2). Even though the data show the monitoring system to be adequate in measuring volume sprayed, there really is no knowledge gained of weed presence. The results were averaged over two seconds and only by hood (averaged across three sensors). The flow sensors simply showed that liquid was flowing through them, and did not indicate which solenoid was activated. Another monitoring system was needed to provide a more accurate weed map.

PROTOTYPE 2

The second prototype relied on a completely different measurement technique than the first. In this prototype spray instances were sensed in the solenoid itself. Valve cartridges were modified to allow signal transference from the solenoid to the monitor. A hole was bored into each valve cartridge and a wire was spliced into the power supply for the solenoid, which was then connected to one of two SW8A switch closure modules (Campbell Scientific, Inc., North Logan, Utah). A Campbell 21X datalogger (Campbell

Scientific, Inc., North Logan, Utah) was used to measure a duty cycle once every second on the switch closure modules. Specific programming instructions in order to make these measurements were also developed (Figure 3).

An experiment almost identical to the one used to test Prototype I was used to test Prototype II. The only change was no spray dye was used, and there were only 16 transects as opposed to 17 in the first experiment. Measurements collected with prototype two were found to have a high degree of variability (Figure 4). Differences between actual and predicted ranged from 12.9 to 655.4 ml. Error ranged from 0.7 to 39.0 percent with an average error of 16.8% (Table 2), more than twice as much error as Prototype I had. Statistical analysis further showed errors in the monitoring systems measurements in that the regression equation has a slope of 0.32 and a R^2 of 0.28 (Figure 5). However, Prototype II did solve a problem in that it allowed for monitoring of each individual sensor.

The reason for this error was not apparent until further tests were run on the electronics. Using an oscilloscope, it was found that the voltage was being rapidly pulsed to the solenoid. This fact was confirmed in communication with the manufacturer. Since the current supplied to the solenoid was not constant, but rather pulsing at a rapid rate, any added resistance in the circuit caused periodic latch failure in the solenoid. Therefore, even though the sensor actually sensed the presence of a weed and the monitoring system detected a spray occurrence, the solenoid did not latch and no liquid was sprayed. Also, it was found that the Patchen™ system controller was at a different ground state than the solenoid. This phenomenon caused further difficulties in duty cycle measurements of the switch closure modules. To correct these problems, Prototype III was developed.

PROTOTYPE III

A final prototype was developed to eliminate the problem with voltage oscillation and subsequent solenoid latch failure and incorrect duty cycle measurements. One main component was changed and another was added. To correct the problem of differing ground states between the Patchen™ system and the switch closure modules, a physical connection was simply eliminated by installing optical relays (Texas Instruments TN426). If traditional physical, latch relays were used, the problem of different ground states would remain. Since the optical relays have no physical connection, this allowed the switch closure modules and the spray nozzles to be completely electrically isolated from each other. In order to correct the second problem of too much resistance in the connection wires, a 12-volt (VDC05) solenoid valve driver cartridge replaced the 5-volt (VC05) solenoid. This configuration eliminated solenoid latch failure, and still allowed for duty cycle measurements to be made.

To test this final prototype, volume measurements were compared to predicted measurements obtained by operating the WAS over a patchily, weedy area. Similar to prior experiments, operating pressure for the sprayer was 138 kPa, provided by a 12 V diaphragm pump, but liquid was sprayed out of a 19-L tank. A short piece of plastic tubing was attached to each external solenoid, and the emitted liquid was caught in individual measuring cups. The liquid in each cup was measured after operating the sprayer for 30 seconds. There was good agreement between the predicted volumes and the actual volumes measured (Figure 7). A regression revealed an equation of $y = 0.9787x + 23.688$ with an R^2 of 0.87. So this final prototype was able to accurately and precisely predict volume output from each nozzle, but there still existed a question of whether or not this logging system could predict actual weed ground cover.

Another experiment was conducted to further test the ability of this final prototype to make ground cover estimates. Four different weed densities (2.5, 5, 7.5, and 10 % ground cover) were distributed randomly over four-15 meter transects. The prototype monitoring system was used to determine ground cover over these different transects. The test was a randomized complete design with eight replications. With all the ground covers there again was very little variation among the replications (Figure 6).

An analysis of variance revealed there was no significant difference among the predicted ground covers in the eight replications for each of the ground covers. However, there was a significant difference in the predicted ground cover measurements and the actual ground cover. This overestimation was likely due to two different factors. The first is the fact that the sensor activates for a set amount of time. So, even if it activates for one second, it has traveled over a considerable distance in that amount of time. Secondly, the sprayer is activated when even a small portion of the infrared beam reflects off of plant material in its field of view (FOV). Adding these two factors together reached the conclusion that there is an offset, which when interpreted from the data yields an average of 5.35 times more ground cover than is actually present. This test provided further evidence that Prototype III accurately determinrd the volume sprayed out of each individual nozzle/sensor combination, but further work should be done to clarify ground cover estimates.

CONCLUSIONS

In order to understand the ecology of weeds and to design future management strategies to improve control tactics, weed scientists now recognize that knowledge of weed spatial distribution is important (Zanin, *et al*., 1998). Past methods of determining weed populations was by a few random counts to estimate the average density of weed species present in a field (Wiles *et al*, 1993). This was time consuming and did not provide an accurate picture of the spatial distribution of weed species (Wiles *et al*, 1993). By utilizing a weed-activated sprayer, measurements can be taken over the entire field in a rapid process. Using the monitoring system developed in this study will allow researchers to gain the necessary knowledge of weed populations to make accurate crop yield loss predictions and future control tactics. Although the monitoring system was successful in predicting herbicide applied, it was unable to determine an exact measurement of ground cover. It was also unable to provide instantaneous weed maps, although post-processed maps were generated. Another drawback is that the monitoring system was not accessible to the driver of the tractor. Future research with this instrument should concentrate on defining and correcting the overestimation problem and integrating the measurement system into a compact, real-time monitor that can allow the equipment operator to monitor system activity and produce weed maps immediately after field spraying.

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Table 1. Predicted and actual volumes, and error for Prototype 1.

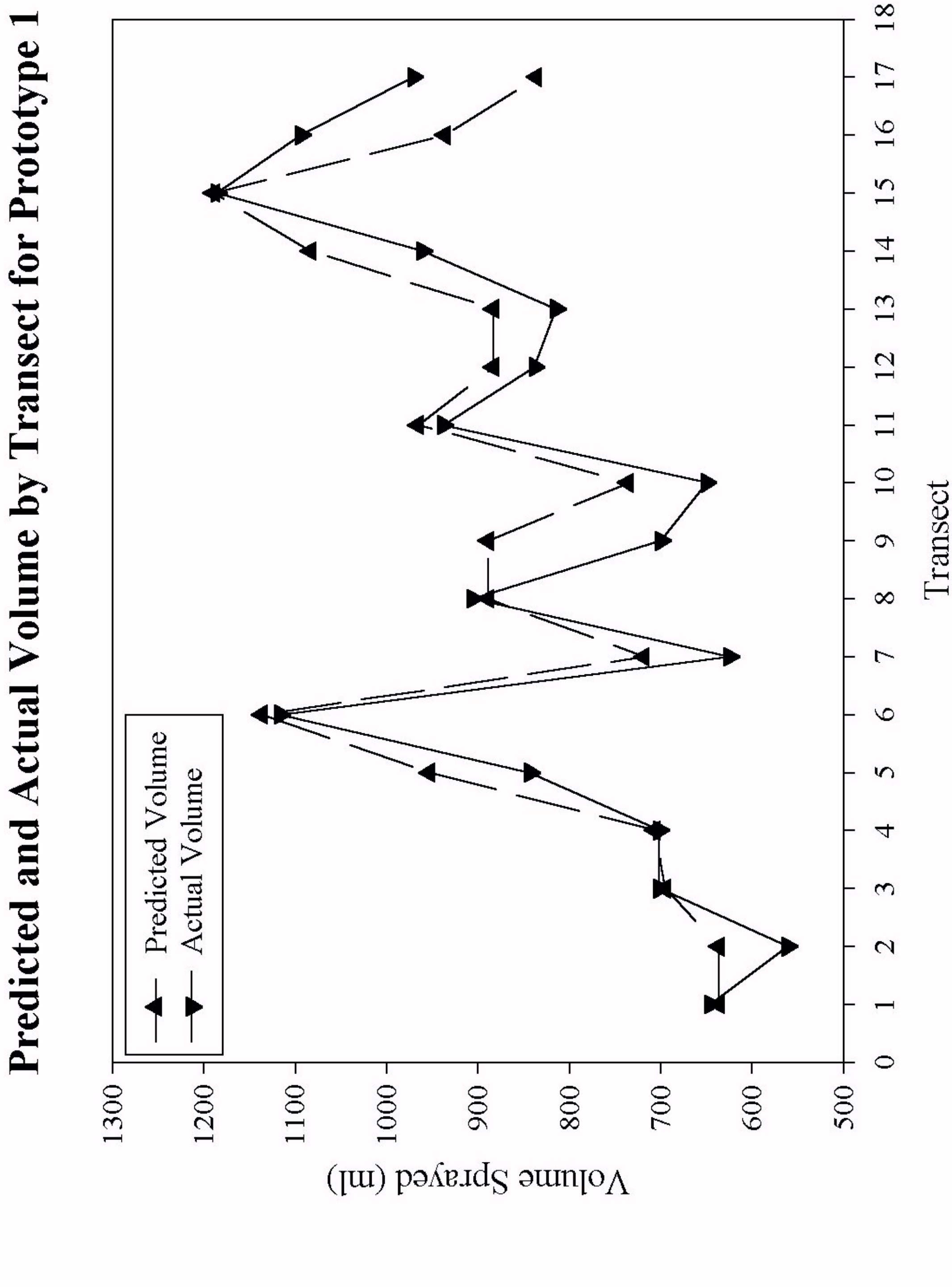
Transect	Predicted (ml)	Actual (ml)	Difference (ml)	Error (%)
1	615.5	646.0	30.5	4.7
2	615.5	561.0	54.5	9.7
3	672.5	702.0	29.5	4.2
4	712.4	702.0	10.4	1.5
5	923.2	843.0	80.2	9.5
6	1099.9	1117.0	17.1	1.5
7	695.3	625.0	70.3	11.2
8	860.5	906.0	45.5	5.0
9	860.5	700.0	160.5	22.9
10	712.4	650.0	62.4	9.6
11	934.6	938.0	3.4	0.4
12	854.8	838.0	16.8	2.0
13	854.8	815.0	39.8	4.9
14	1048.6	961.0	87.6	9.1
15	1151.2	1186.0	34.8	2.9
16	906.1	1094.0	187.9	17.2
17	809.2	971.0	161.8	16.7
Average	842.8	838.5	64.3	7.8

Table 2. Predicted and actual volumes, and error for Prototype 2.

Transect	Predicted (ml)	Actual (ml)	Difference (ml)	Error (%)
1	1681.4	1026.0	655.4	39.0
2	1648.0	1073.0	575.0	34.9
3	1320.0	1106.0	214.0	16.2
4	1767.4	1425.0	342.4	19.4
5	1833.4	1480.0	353.4	19.3
6	1827.9	1341.0	486.9	26.6
7	1762.5	1457.0	305.5	17.3
8	1692.8	1454.0	238.8	14.1
9	1622.8	1392.0	230.8	14.2
10	1530.3	1476.0	54.3	3.5
11	1219.7	1560.0	340.3	27.9
12	1833.5	1645.0	188.5	10.3
13	1895.1	1908.0	12.9	0.7
14	1927.8	1903.0	24.8	1.3
15	1912.1	2039.0	126.9	6.6
16	1879.4	2200.0	320.6	17.1
Average	1709.6	1530.3	279.4	16.8

FIGURE LEGEND

FIGURE 1. Predicted spray volume found with Weed-activated sprayer and actual volume sprayed plotted versus transect for Prototype I.



Predicted and Actual Volume by Transect for Prototype 1
Predicted Volume
Actual Volume
Volume Sprayed (ml)
1300
1200
1100
1000
900
800
700
600
500
Transect
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

FIGURE LEGEND

FIGURE 2. Plot of regression line on predicted volume found with the weed-activated sprayer as a function of the actual volume sprayed for Prototype I.

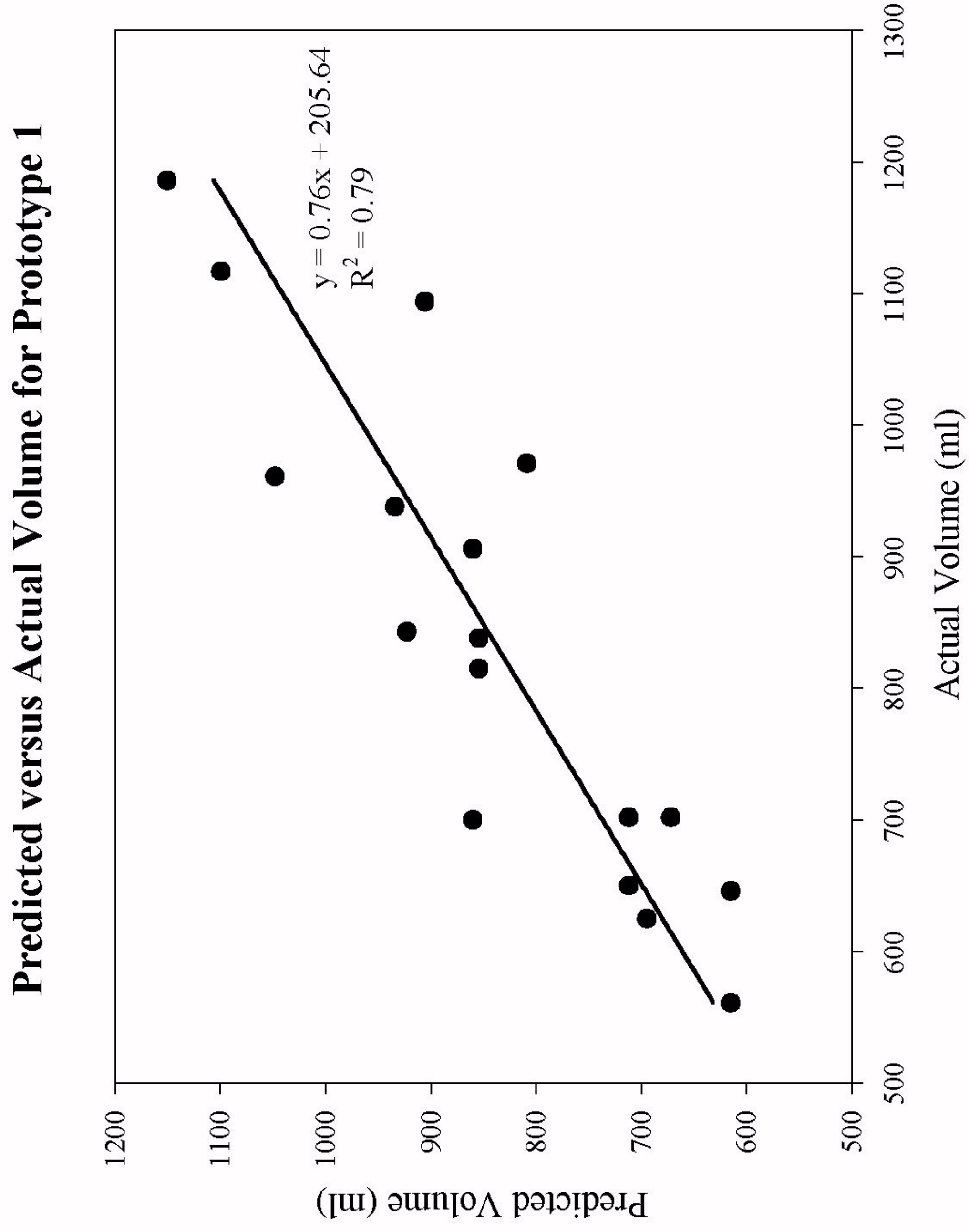

Predicted versus Actual Volume for Prototype 1
y = 0.76x + 205.64
R2 = 0.79
Predicted Volume (ml)
Actual Volume (ml)
500
600
700
800
900
1000
1100
1200
1300

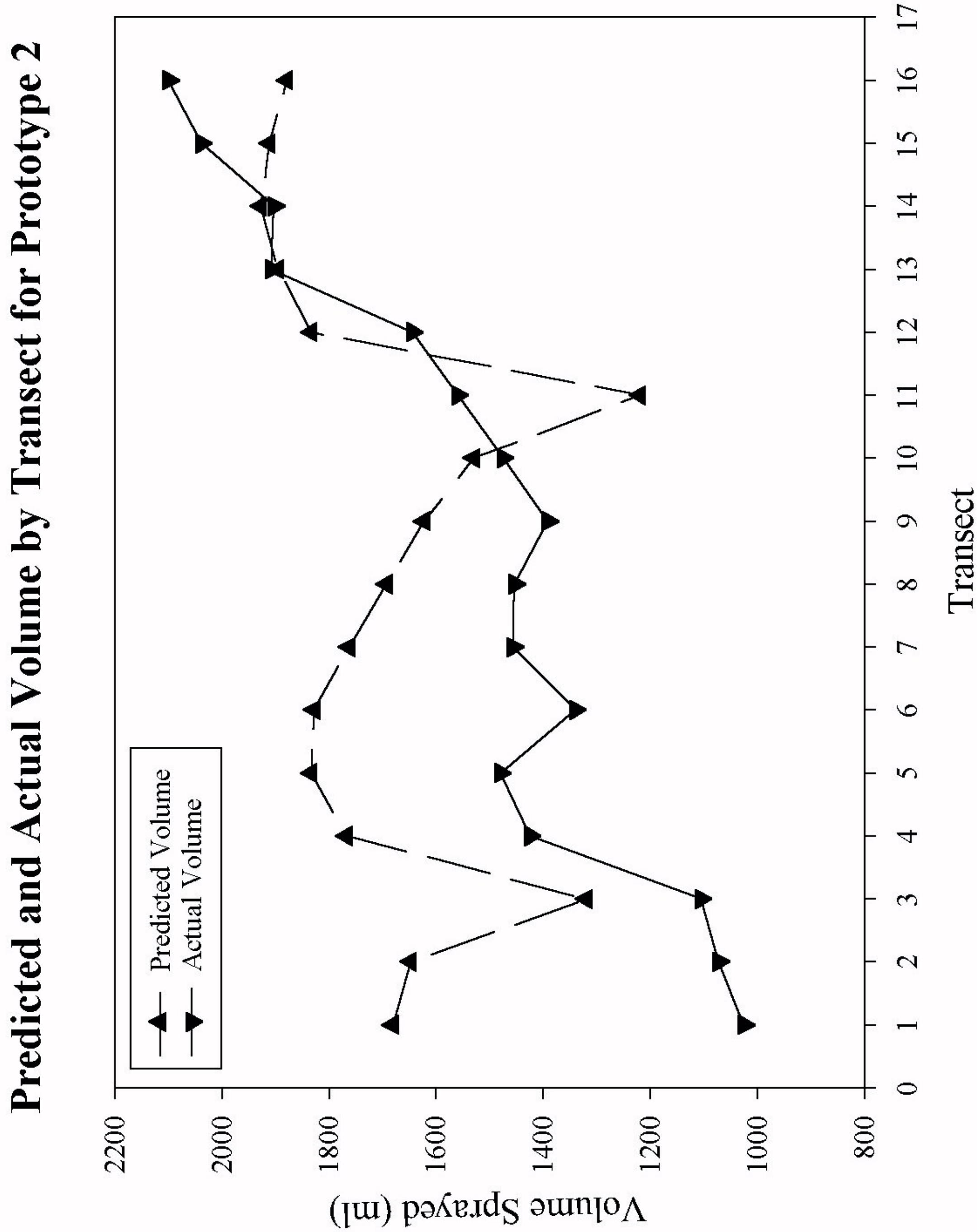
FIGURE LEGEND

FIGURE 3. Program for measuring data from two SDM-SW8A's

```
*Table 1 Program
01: 1.0       Execution Interval (seconds)

1:  Time (P18)
1: 0          Tenths of seconds into current minute (Max 600)
2: 10         Mod/By
3: 10         Loc [ MDSECONDS ]

2:  SDM-SW8A (P102)
1: 5          Reps
2: 0          Address
3: 1          Duty cycle function
4: 1          Channel
5: 11         Loc [ DUTY_C_1  ]
6: 1.0        Mult
7: 0.0        Offset

3:  SDM-SW8A (P102)
1: 4          Reps
2: 10         Address
3: 1          Duty cycle function
4: 1          Channel
5: 16         Loc [ DUTY_C_6  ]
6: 1.0        Mult
7: 0.0        Offset

4:  IF (X<=>F) (P89)
1: 10         X Loc [ MDSECONDS ]
2: 1          =
3: 0.0        F
4: 10         Set Output Flag High

5:  Real Time (P77)
1: 0021       Hour/Minute,Seconds (Midnight = 2400)

6:  Sample (P70)
1: 9          Reps
2: 11         Loc [ DUTY_C_1  ]

7:  Serial Out (P96)
1: 30         SM192/SM716/CSM1
```

FIGURE LEGEND

FIGURE 4. Predicted spray volume found with Weed-activated sprayer and actual volume sprayed plotted versus transect for Prototype II.



Predicted and Actual Volume by Transect for Prototype 2
Predicted Volume
Actual Volume
Volume Sprayed (ml)
Transect
2200
2000
1800
1600
1400
1200
1000
800
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

FIGURE LEGEND

FIGURE 5. Plot of regression line on predicted volume found with the weed-activated sprayer as a function of the actual volume sprayed for Prototype II.

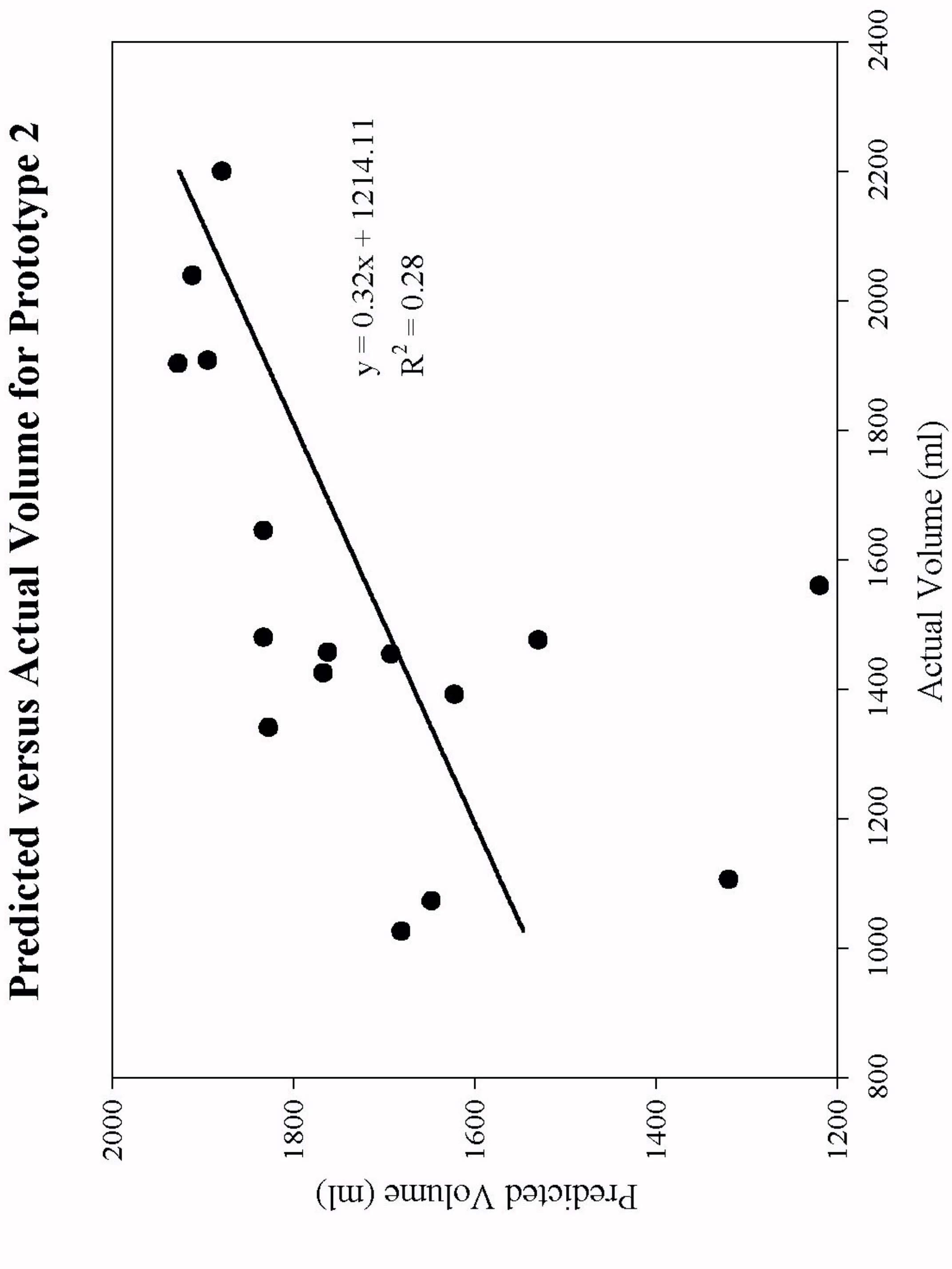

Predicted versus Actual Volume for Prototype 2
y = 0.32x + 1214.11
R^2 = 0.28
Actual Volume (ml)
Predicted Volume (ml)
800
1000
1200
1400
1600
1800
2000
2200
2400
1200
1400
1600
1800
2000

FIGURE LEGEND

FIGURE 6. Observed ground cover found with Prototype III plotted by the actual ground cover.

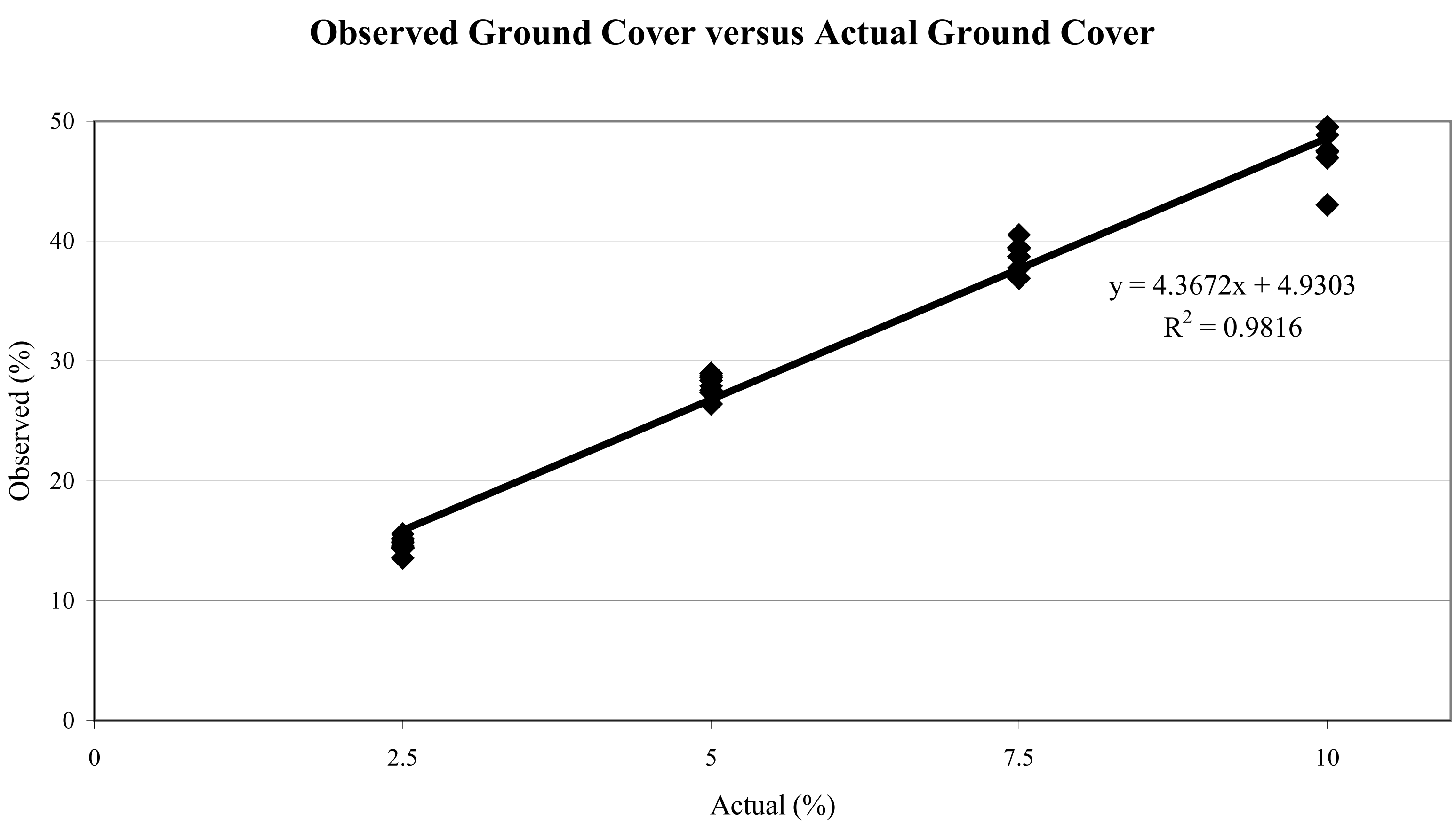
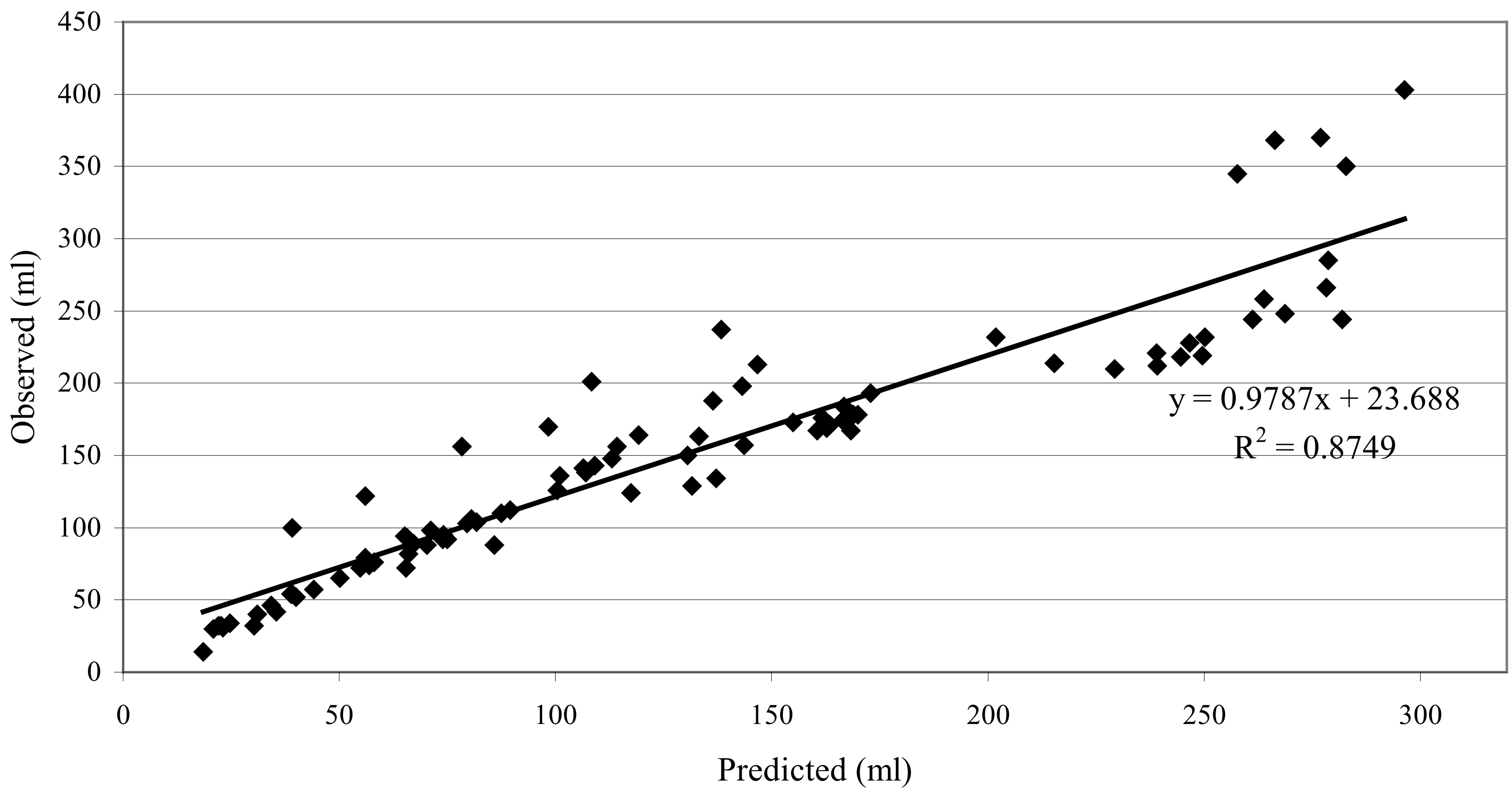

Observed Ground Cover versus Actual Ground Cover
Observed (%)
50
40
30
20
10
0
0
2.5
5
7.5
10
Actual (%)
y = 4.3672x + 4.9303
R2 = 0.9816

FIGURE LEGEND

FIGURE 7. Accuracy of volume predictions made with the Patchen™ monitoring. The observed volume measurements plotted against those predicted by Prototype III.

Observed Volume Measurements versus Predicted Volumes from Weed-activated Sprayer Monitoring System



SECTION III.

MEASURING WEED GROUND COVER USING TRADITIONAL SCOUTING, IMAGE ANALYSIS AND A WEED-ACTIVATED SPRAYER[1]

[1]W.J. Parks and D.C. Bridges. To be submitted to *Weed Technology*

ABSTRACT

Vegetative ground cover (GC) was compared by 1) visually estimating GC in many random one-meter by one-meter quadrants, 2) digital image analysis of the same one-meter square quadrants, and 3) continuous measurements of GC using a weed-activated sprayer (WAS). The percentage of ground cover determined by image analysis correlated positively with that made by visual estimations ($r = 0.92$ and 0.93). Error was inversely proportional to percentage of weed ground cover. Nonrandom measurements made with the WAS had little correlation with random estimates in one field ($r = 0.69$) and very little correlation in the other two ($r = 0.14$ and 0.42). Although random sampling of weed densities is precise in small areas, it is not indicative of actual densities in whole fields due the patchy nature of weed distributions. Ground cover estimates made with the WAS were more representative of the entire field, but there was an overestimation that needs to be investigated in future studies.

INTRODUCTION

Growers, land managers, and consultants have long recognized the spatial heterogeneity in fields, yet resources, including herbicides, are applied to whole fields despite this recognition (Mortensen *et al*., 1998). Most weed-control control strategies can be categorized as either a "control at any price" strategy or an "economic threshold" strategy (Hurle, 1998). In the former all weeds are sprayed regardless of density or distribution, while in the latter weeds are only controlled if the net economic gain in yield exceeds the cost of the control method. The economic threshold strategy uses decision models to determine the yield loss by assuming a regular or random distribution (Wiles *et al*., 1992) but it does not take into account weed distribution, only weed density. Since weeds generally exhibit a patchy (aggregated) distribution (Hofsten, 1947; Marshall, 1988; Thorton *et al*., 1990; Navas, 1991; Thompson *et al*., 1991; Mortensen *et al*., 1992; Stafford and Miller, 1993; Donald, 1994; Rew *et al*., 1996) and conventional herbicide application is made as a broadcast treatment of a single rate over the entire field, an economic threshold based on density alone can result in over-application of herbicide (Hughes, 1989; Thorten *et al*., 1990). Rutherford (1985) described the wastefulness of broadcast pesticide application as "the least efficient industrial process on earth."

Treating only part of the area infested by weeds can result in significant herbicide savings (Ahrens, 1994; Audsley, 1993; Rew *et al*., 1996; Green, 1997). Selectively spraying chemicals only where weeds are present is not a new idea, but has been limited in the past to manually turning the sprayer on and off or spot spraying with a hand sprayer (Hanks and Beck, 1998). However, it is also often difficult for humans to accurately perform such tasks and operators who don't have financial stock in the operation have no motivation to do so (Schueller and Wang, 1994). According to Schueller (1992), modern, selective, or patch, spraying systems can perform as either temporally-separate (previously acquired maps (Brown and Steckler, 1995; Green, 1997;

Tredaway *et al*., 1998) or automatic (real-time) control using plant sensing equipment. In order to determine weed densities and distributions for weed maps, an individual must conduct a survey of the weeds in a field (Mumford and Norton, 1987). Just as in traditional economic threshold strategies, the scout estimates the average densities of weed species present, and this information is used to make post-emergence control decisions (Wiles *et al*., 1993). However, randomly counting weeds is time consuming (Wiles, *et al*, 1993), and the aggregated nature of weed populations can hinder accurate estimations of weed densities (Marshall, 1988; Wiles *et al.*, 1993). "Weed-activated sprayers" (WAS) that automatically sense the presence of weeds and deliver a prescribed dose of herbicide have been developed (Haggar *et al*., 1983; Felton *et al*., 1991; Shearer and Jones, 1991; Hanks and Beck, 1998) with varying degrees of success and acceptance. Although real-time control is efficient and less time consuming, in contrast to weed mapping, there is no record of the location of weed populations. In order to understand the ecology of weeds and to design future management strategies to improve control tactics, weed scientists now recognize that knowledge of weed spatial distribution is important (Zanin, *et al*., 1998). Since field scouting is time consuming, there is a potential for the use of WAS to map weeds. This would provide a fast, efficient method of whole field scouting to provide the knowledge of weed spatial distribution.

The objectives of this study were to determine the accuracy and precision of random quadrant sampling of weed ground cover by human observers, and to compare these estimates to the spatial variability of weed populations in a field found using a weed activated sprayer.

MATERIALS AND METHODS

Random Visual Estimates. Field surveys were conducted on three, 0.3-ha fields at the University of Georgia Bledsoe Farm in Pike County, Georgia. Fifteen, sixteen, and seventeen transects, 45.7 meters long, were spaced 3 meters apart in each field respectively. Three observers made independent estimates of the percent of ground covered with green vegetation in a 1-meter square frame at five random positions along each transect (Zanin, *et al*., 1998). Measurement locations were selected by randomly picking five numbers from 2 to 45 (corresponding to one-meter increments along the transect) using the random number generator in a spreadsheet program (Microsoft Excel, Microsoft Corp,). A total of 75, 80, and 85 sampling units were identified in each of the three fields respectively, each one characterized by the spatial coordinates of each measurement point. For Field D1 and E4 estimates were conducted in the field. For Field K8 visual estimations were made on digital images of the frames, cast by an LCD projector, instead of in the field.

Random Image Measurements. Digital, color images were made using a Sony digital camera (Sony Mavica) at a resolution of 1024 pixels by 768 pixels to give the highest resolution possible and good contrast between plants and soil. Images were taken of each 1-meter square frame from a stepladder placed over the frame immediately following ground cover estimates. Images were loaded onto the personal computer (PC) and cropped to include just the frame using the computer imaging software Paint Shop Pro (Paint Shop Pro, JASC Inc., Eden Prairie, Minnesota). This process was performed to allow no plant material outside the frame to show in the picture. Then each image was quantitatively analyzed for percent ground cover (Beverly, 1996) using SigmaScan Pro computer software (SigmaScan Pro, SPSS Inc., Chicago, Illinois).

Non-random WAS Measurements. The final weed survey was made using the Patchen™ WeedSeeker weed-activated sprayer (Patchen™ Inc., Mayfield Equipment Co., Ukiah, California). Originally developed for application in orchards, the WAS has been adapted to row crop agriculture by using spray hoods to house the sensors (Hanks and Beck, 1998). Although the WeedSeeker was designed to spray weeds detected by the sensors, it possesses no recording capabilities. Parks (2000) developed a monitoring system in order to record spray occurrences with the Patchen™ WeedSeeker. In combination with position data obtained using a differentially corrected global positioning system (DGPS) (Omnistar 3000, J.E. Chance and Assoc., Houston, Texas) the duration and location of every spray occurrence by each nozzle was accurately recorded. Three hoods (having three sensor units each) mounted 1 meter apart on a three-point hitch tool bar were used to selectively spray each transect where measurements had been taken previously. The middle hood was centered on each transect, thus measuring 0.7 meter of the measurement frame, or about 70%. Each hood was calibrated to apply 60 L/ha over the 0.7-m-wide area covered by each hood at a speed of 4.8 km/h. Three WeedSeeker Model PhD 612 sensors independently controlled a TJ6205 flat fan nozzle in each hood. An operating pressure of 138 kPa for the sprayer was provided by a 12 V diaphragm pump, and liquid was dispensed out of three-liter bottles. Water with a spray dye was used as a visual indicator of vegetation that was sensed and sprayed. The system was charged to fill all plumbing and each run began with a known volume. Remaining volume was recorded for each spray pass to compare with the volume predicted by the monitoring system. A summary of ground cover determinations is provided in Table 1.

RESULTS AND DISCUSSION

Repeatability of Visual Estimates. There appeared to be little variation among the human estimates of percent ground cover from field D1 (Figure 1). An analysis of variance, performed using SAS (SAS, 1987), found that there was indeed no significant difference in the estimates. Similar results were found in the data from Field E4 (Figure 2). Statistical analysis again showed no significant difference in the estimates of each observer. In Field K8, where post image-viewed estimates were made, there was some difference evident (Figure 3). An analysis of variance revealed there was a significant difference in the ground cover estimates. It is unlikely this difference was due to unreliable observation techniques. The difference was actually due to decreased concentration in a relaxed setting and poor image visibility from the image projection. Visual quality was often much better in the field than when viewing a digital image. When an analysis of variance was conducted on the pooled data, no significant differences were found. So the estimations of ground cover were very similar to each other, supporting the conclusion that human observations were repeatable, or precise, but the accuracy, or level of correctness, was still unknown.

Comparison of Visual Estimates and Image Analysis. Results from the image analysis of percent ground cover were compared against the mean visual estimates for each transect. In Field E4 there was good correlation between visual estimates and image analysis measurements (Figure 4). A regression analysis (SAS, 1987) resulted in an equation of $y = 1.13x - 2.92$ with a R^2 of 0.85. Similar results were found in Field K8 (Figure 5). A regression analysis of this data resulted in an equation of $y = 0.91 +1.03$ with a R^2 of 0.86. Although not a perfect correlation, there was good agreement between visual estimations and the actual ground cover determined by the image analysis.

There were variations in the transect measurements in fields E4 (Table 2) and K8 (Table 3), with the visual ground cover estimates being slightly higher overall. This variation can be seen in the percent error determined by dividing the difference in the image (actual) and the visual (observed) measurements by the image (Tables 2 and 3). The errors range from 5.7% to 44.8% in E4 and from 0.0% to 160.0% in K8. In E4, the observed value was larger than the actual in nine of the sixteen transects (Table 2). It was inferred that no bias existed between the techniques. The average difference was 0.8, while the mean absolute difference (MAD) was 4.04. In field K8, the average difference was 0.4 while the MAD was 1.2 (Table 3) indicating that there was very good agreement between the two techniques.

The 160.0% value in field K8 is an outlier and is simply due to the very small amount of vegetation in that quadrant (1.0%) which inflates the error. This outlier does, however help to illustrate the fact that as weed density increases, the ability of the observer to accurately estimate ground cover increases (or percent error decreases). Plotting percent error as a function of percent ground cover (Figures 6 and 7) shows a strong trend that error is inversely proportional to percent ground cover. This idea is intuitive in that the more of the area that is visibly covered with vegetation, the easier it is to estimate how much of the area is covered. So traditional scouting techniques do provide accurate estimates of the weed density in a small area. Yet, in these fields there were five, 1-m^2 samples taken out of an almost 50 m^2 transect, which is about ten percent of the total area. Most scouting techniques involve approximately 10 to 20 measurements per 40 ha. In order to cover as much area in a typical field as was covered in the test area, almost 40,000 measurements would be required. Therefore, can a small number of random samples represent the actual weed density in a field? In other words, even though random sampling may provide precise measurements that are accurate in small areas, do the average of these measurements provide an accurate representation of the entire field? The measurements obtained using the WAS helped answer this question.

WAS Measurements. Comparing the measurements of ground cover made with the WAS to those of the random estimates resulted in large differences in field D1 (Figure 8), E4 (Figure 9) and K8 (Figure 10). There was an average difference of 26.3%, 55.5%, and 17.5% between WAS measurements and visual estimations in Fields D1, E4, and K8 respectively (Tables 4, 5, and 6). The average differences between the WAS measurements and image observations were very similar to the visual comparisons in E4 (56.2%) and K8 (17.9%) (Tables 5 and 6). The average percent error was also high in each field, ranging from 66.5% for field E4 to 73.3 % for field K8 (Tables 4, 5 and 6). These large differences would ideally be explained by the fact that by using the weed activated sprayer to measure ground cover, 100% of the transect was measured as opposed to just 10% with the random estimates. It appeared that the nonrandom WAS measurements provided a very large improvement in the ability to accurately measure the ground cover along each transect. This fact was supported in the plot of ground cover measured with the WAS versus that of the visual analysis for field D1 (Figure 11). A regression analysis found an equation of $y = 0.73x + 29.33$ with a R^2 of 0.48. Even stronger evidence was found in fields E4 (Figure 12) and K8 (Figure 13), which plot the regression equation for E4 ($y = 0.72x + 54.78$) and K8 ($y = 0.88x + 18.61$). These equations had a R^2 of 0.02 and 0.18 respectively. Although the measurements were precise, there was no real way to tell if the WAS measurements were accurate or not.

The data show that there is an offset between the nonrandom WAS measurements and the random visual and image estimates. This can be due to the fact that there is inherent overestimation in the Patchen™ monitoring system (Parks, 2000), and thus the sprayer is not accurate. To determine if there was simply an overestimation, the bias was removed by subtracting the mean of all transects from each transect mean (Figures 14, 15, and 16). After normalization the data appeared to be more closely correlated, but there were still some large differences in some transects. A regression analysis of the image and observed ground covers versus the WAS measurements revealed almost no correlation in the overall model. Although random sampling may provide precise measurements of weed ground cover and can even be accurate in small areas, it does not provide an accurate nor precise portrayal of the actual weed ground cover in a whole field. Since the WAS measured the entire area, it has a greater probability to encounter weeds patches and make a more accurate measurement of true field conditions.

Broadcast herbicide treatment is often an inefficient application method of weed control, yet it is the norm in most fields. Weeds are generally patchy or non-randomly distributed in agricultural fields, yet traditional scouting techniques assume a random distribution and herbicides are applied based on this assumption. Although scouting the entire field would be the ideal approach, this is impractical on a large scale. In this study, over 75 random samples were taken out of 0.7 ha. This was a very large sample size, the individual measurements were precise and gave an accurate estimate of ground cover in the sampled area. Although random sampling by human observers did provide a precise estimate of the ground cover in a small area, it did not provide an accurate representation of the ground cover in an entire field. Using a weed-activated sprayer to map weeds does provide much more precise knowledge of the spatial distribution of weeds in a field because the sample area is infinitely large. However, the accuracy of these measurements needs more study. Using this knowledge to make more educated weed control decisions can help reduce herbicide use and provide more efficient and less expensive weed management programs. The use of the WAS in this study did not provide knowledge of the species present, just the amount of ground covered by green vegetation. Future research should focus on determining the exact accuracy of ground cover measurements with this instrument and interspecies differentiation in order to make recommendations specific to species for maximum weed control.

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Table 1. Summary of method by which weed ground cover estimates were determined.

Field	# of Transects	Visual Estimates	Image Analysis	WAS[a]
D1	17	Yes	No	Yes
E4	16	Yes	Yes	Yes
K8	15	Yes	Yes	Yes

[a] WAS - Weed-activated Sprayer

Table 2. Visual estimations versus image analysis of weed ground cover (Field E4)

Transect	Actual Ground Cover (%)	Observed Ground Cover (%)	Difference Obs - Act	Standard Deviation	Error (%)
1	13.8	16.7	2.9	2.1	21.0
2	14.2	8.3	- 5.9	4.2	41.5
3	7.6	9.6	2.0	1.4	26.3
4	17.0	13.2	- 3.8	2.7	22.4
5	48.0	55.0	7.0	4.9	14.6
6	22.8	20.1	- 2.7	1.9	11.8
7	32.8	30.5	- 2.3	1.6	7.0
8	25.4	22.0	- 3.4	2.4	13.4
9	25.2	22.4	- 2.8	2.0	11.1
10	40.0	34.7	- 5.3	3.7	13.3
11	39.2	42.1	2.9	2.1	7.4
12	24.2	29.3	5.1	3.6	21.1
13	23.0	24.7	1.7	1.2	7.4
14	34.0	36.8	2.8	2.0	8.2
15	35.0	37.0	2.0	1.4	5.7
16	27.0	39.1	12.1	8.6	44.8
Mean	26.8	27.6	0.8		17.3
MAD*			4.0		

*Mean Absolute Difference - calculated by taking the mean of the absolute values.

Table 3. Visual estimations versus image analysis of weed ground cover (Field K8)

Transect	Actual Ground Cover (%)	Observed Ground Cover (%)	Difference Obs - Act	Standard Deviation	Error (%)
1	8.2	6.7	- 1.5	1.1	18.3
2	9.4	9.4	0	0	0.0
3	7.0	5.9	- 1.1	0.8	15.7
4	7.6	6.6	- 1.0	0.7	13.2
5	5.8	4.4	- 1.4	1.0	24.1
6	13.2	12.5	- 0.7	0.5	5.3
7	8.4	9.3	0.9	0.6	10.7
8	4.8	6.6	1.8	1.3	37.5
9	4.6	5.7	1.1	0.8	23.9
10	2.0	3.1	1.1	0.8	55.0
11	12.0	15.0	3.0	2.1	25.0
12	2.6	3.9	1.3	0.9	50.0
13	5.2	5.7	0.5	0.4	9.6
14	4.0	4.9	0.9	0.6	22.5
15	1.0	2.6	1.6	1.1	160.0
Mean	6.4	6.8	0.4		31.4
MAD*			1.2		

*Mean Absolute Difference - calculated by taking the mean of the absolute values.

Table 4. Weed Activated Sprayer Measurements versus Visual Observations of Weed Ground Cover (Field D1)

Transect	WAS[a] Ground Cover (%)	Observed Ground Cover (%)	Difference WAS - Obs	Error[b] (%)
1	27.6	2.9	24.6	89.4
2	27.6	3.0	24.6	89.1
3	30.1	16.1	14.0	46.4
4	31.9	14.5	17.4	54.4
5	41.3	10.4	30.9	74.8
6	49.2	11.9	37.4	75.9
7	31.1	4.7	26.5	85.0
8	38.5	6.8	31.7	82.3
9	38.5	8.9	29.6	76.8
10	31.9	7.5	24.4	76.4
11	41.8	15.5	26.4	63.0
12	38.3	8.9	29.4	76.8
13	38.3	8.2	30.1	78.6
14	46.9	20.7	26.3	56.0
15	51.5	30.3	21.2	41.1
16	40.6	12.7	27.8	68.6
17	36.2	11.9	24.4	67.2
Mean	37.7	11.5	26.3	70.7

[a] Weed Activated Sprayer

[b] Percent error (WAS - Observed)/WAS*100

Table 5. Weed Activated Sprayer Measurements versus Visual and Image Observations of Weed Ground Cover (Field E4)

Transect	WAS[a] Ground Cover (%)	Observed Image Ground Cover (%)	Observed Visual Ground Cover (%)	Difference WAS - Image	Difference WAS - Visual	Error[b] (%)	Error[c] (%)
1	82.0	13.8	16.7	68.2	65.3	83.2	79.6
2	80.3	14.2	8.3	66.1	72.0	82.3	89.7
3	64.3	7.6	9.6	56.7	54.7	88.2	85.1
4	86.1	17.0	13.2	69.1	72.9	80.3	84.7
5	89.4	48.0	55.0	41.4	34.4	46.3	38.5
6	89.1	22.8	20.1	66.3	69.0	74.4	77.4
7	85.9	32.8	30.5	53.1	55.4	61.8	64.5
8	82.5	25.4	22.0	57.1	60.5	69.2	73.3
9	79.1	25.2	22.4	53.9	56.7	68.1	71.7
10	74.6	40.0	34.7	34.6	39.9	46.4	53.5
11	59.5	39.2	42.1	20.3	17.4	34.1	29.2
12	89.4	24.2	29.3	65.2	60.1	72.9	67.2
13	92.4	23.0	24.7	69.4	67.7	75.1	73.3
14	94.0	34.0	36.8	60.0	57.2	63.8	60.8
15	93.2	35.0	37.0	58.2	56.2	62.4	60.3
16	87.2	27.0	39.1	60.2	48.1	69.1	55.2
Mean	83.1	26.8	27.6	56.2	55.5	67.3	66.5

[a] Weed Activated sprayer

[b] Percent error (WAS - Image)/WAS*100

[c] Percent error (WAS - Visual)/WAS*100

Table 6. Weed-activated Sprayer Measurements versus Visual and Image Observations of Weed Ground Cover (Field K8)

Transect	WAS[a] Ground Cover (%)	Observed Image Ground Cover (%)	Observed Visual Ground Cover (%)	Difference Was - Image	Difference WAS - Visual	Error[b] (%)	Error[c] (%)
1	16.4	8.2	6.9	8.2	9.5	50.0	58.1
2	24.1	9.4	9.4	14.7	14.7	61.0	61.0
3	36.3	7.0	5.9	29.3	30.3	80.7	83.6
4	40.0	7.6	6.6	32.4	33.4	81.0	83.5
5	28.4	5.8	4.4	22.6	24.0	79.6	84.5
6	29.4	13.2	12.5	16.2	16.9	55.1	57.6
7	29.5	8.4	9.3	21.1	20.1	71.5	68.3
8	23.6	4.8	6.6	18.8	17.0	79.7	72.0
9	17.7	4.6	5.7	13.1	12.0	74.1	67.7
10	19.1	2.0	3.1	17.1	16.0	89.5	83.6
11	23.9	12.0	15.0	11.9	8.9	49.8	37.2
12	23.1	2.6	3.9	20.5	19.3	88.8	83.3
13	18.0	5.2	5.7	12.8	12.4	71.2	68.6
14	18.5	5.0	4.9	13.5	13.6	73.0	73.7
15	16.6	1.0	2.6	15.6	14.0	94.0	84.3
Mean	24.3	6.5	6.8	17.9	17.5	73.3	71.1

[a] Weed Activated Sprayer

[b] Percent error (WAS - Image)/WAS*100

[c] Percent error (WAS - Visual)/WAS*100

FIGURE LEGEND

FIGURE 1. Visual estimations of percent ground cover from three different observers plotted versus transect for Field D1.

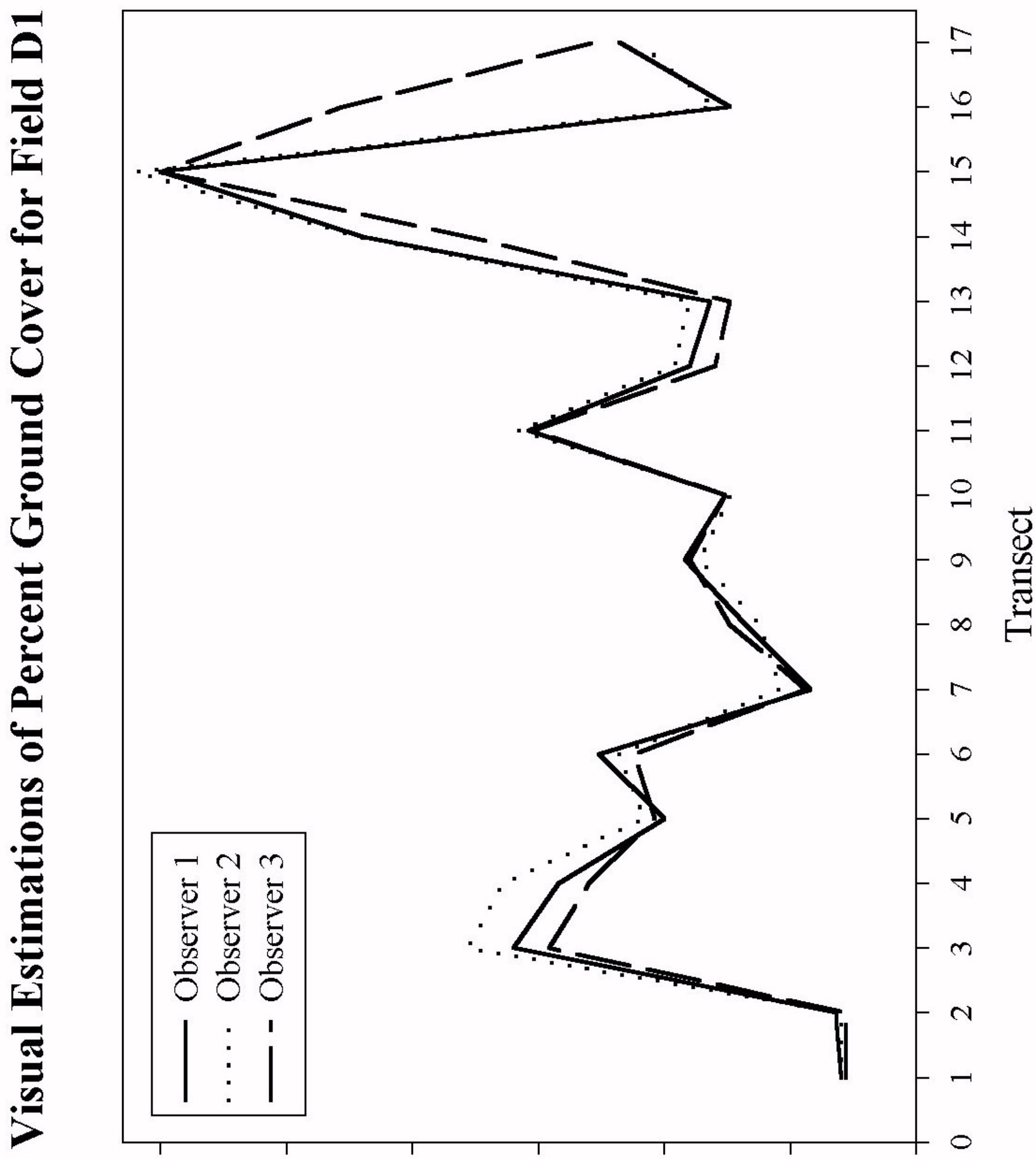

Visual Estimations of Percent Ground Cover for Field D1
Observer 1
Observer 2
Observer 3
Ground Cover (%)
0
5
10
15
20
25
30
Transect
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

FIGURE LEGEND

FIGURE 2. Visual estimations of percent ground cover from three different observers plotted versus transect for Field E4.

Visual Estimations of Percent Ground Cover for Field E4

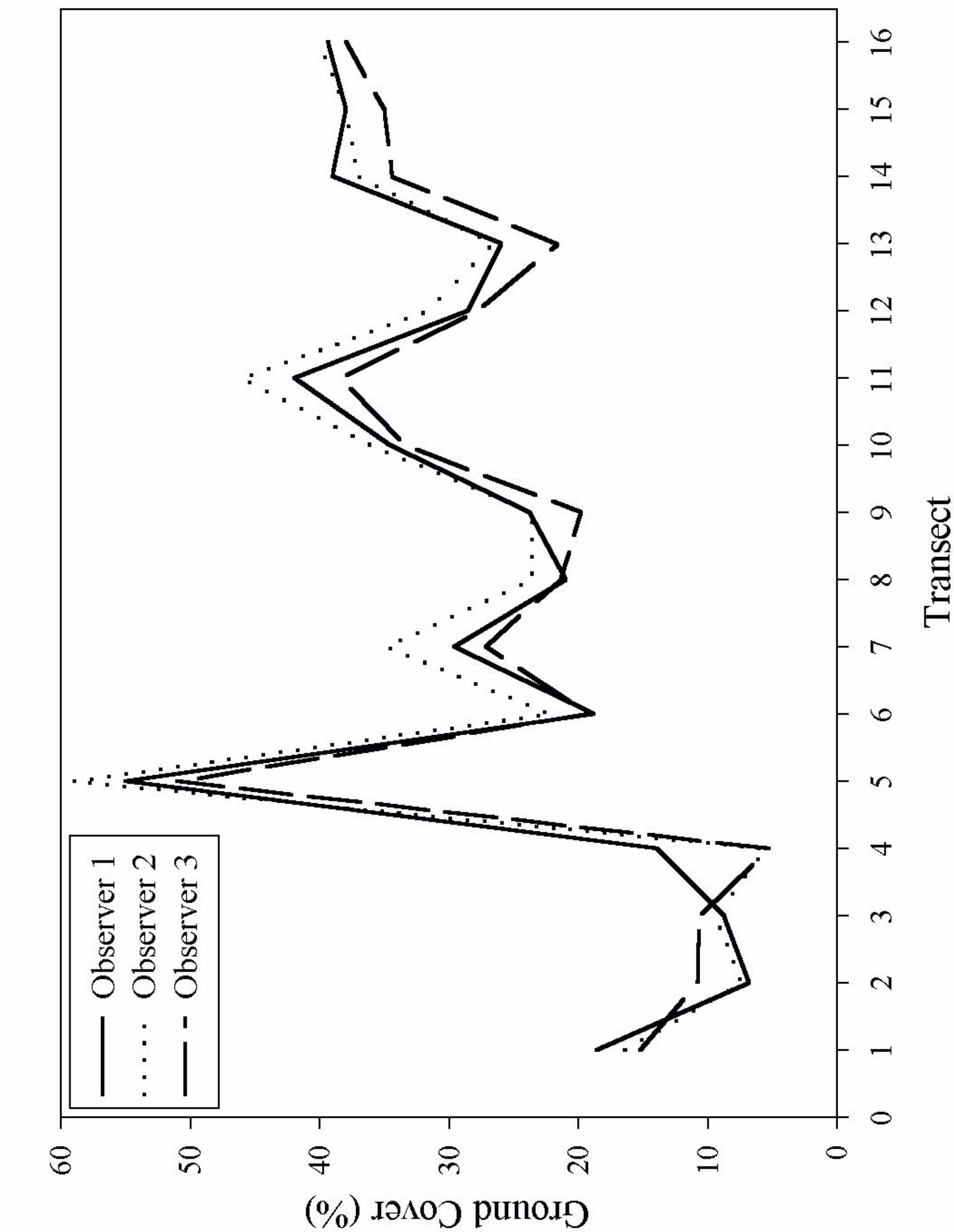


FIGURE LEGEND

FIGURE 3. Visual estimations of percent ground cover from three different observers plotted versus transect for Field K8.

Visual Estimations of Percent Ground Cover for Field K8

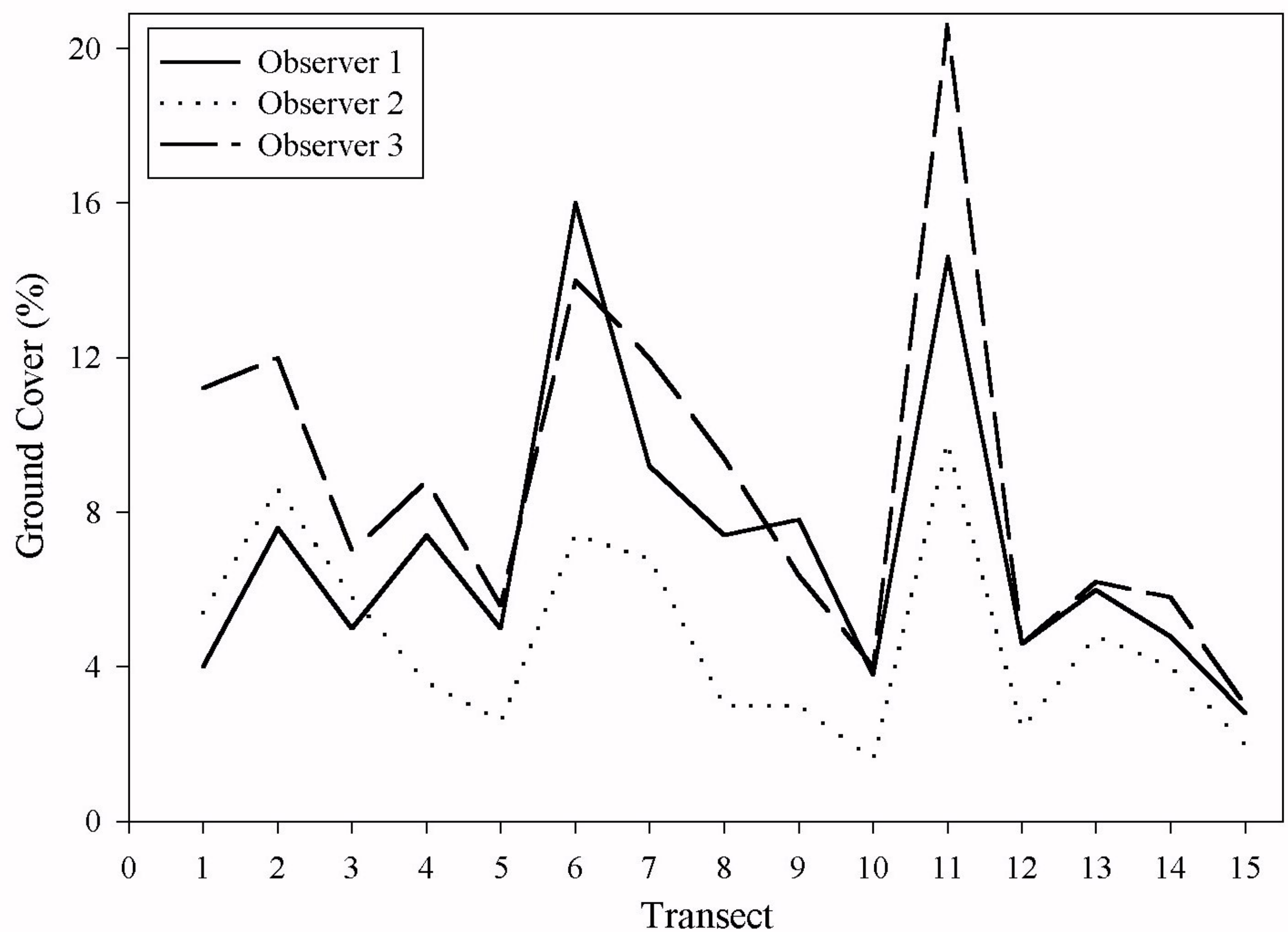


FIGURE LEGEND

FIGURE 4. Mean visual estimations of percent ground cover from three different observers plotted versus image analysis of percent ground cover for Field E4.

Visual Estimations Versus Image Analysis of Percent Ground Cover for Field E4

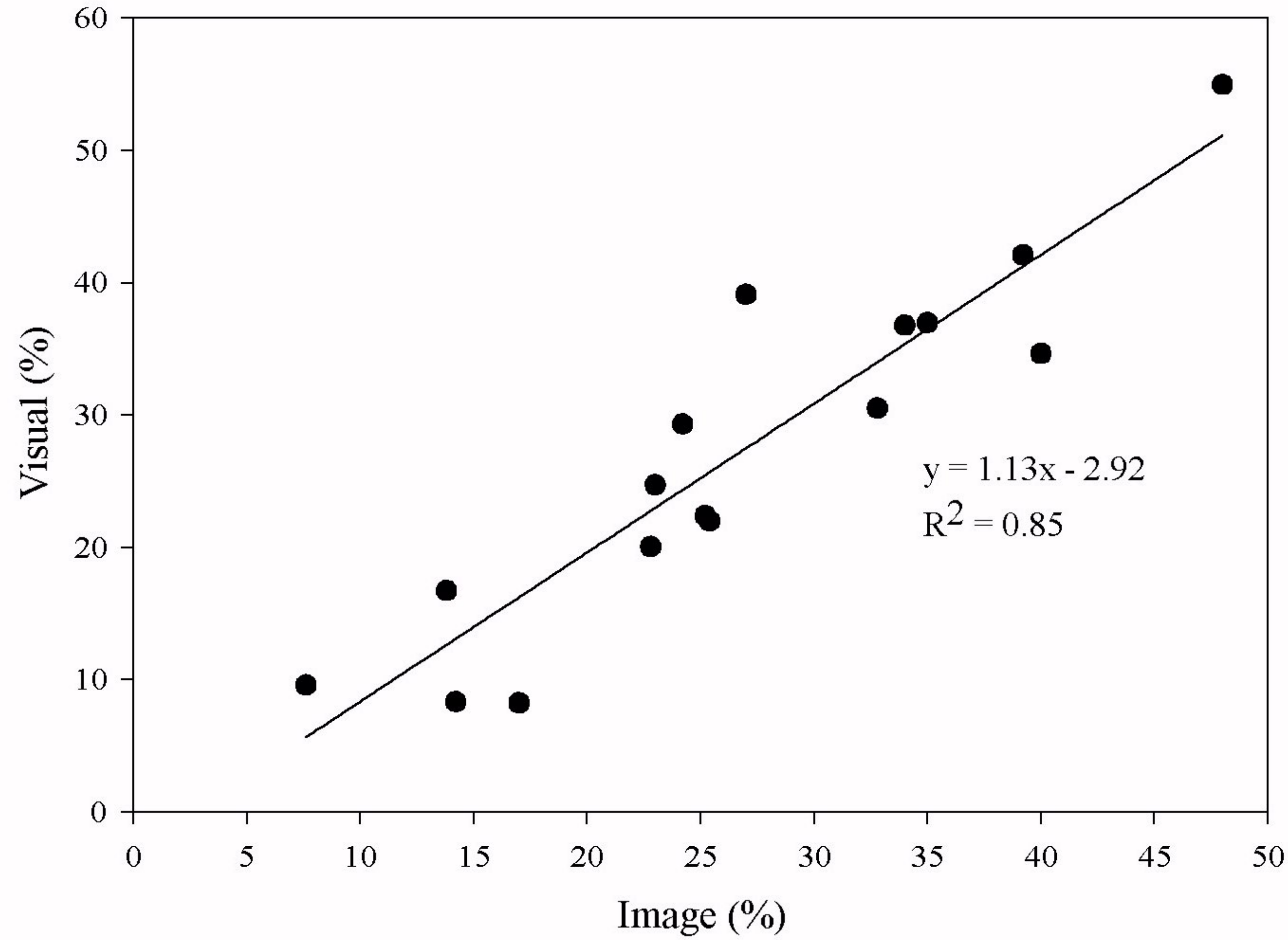


FIGURE LEGEND

FIGURE 5. Mean visual estimations of percent ground cover from three different observers plotted versus image analysis of percent ground cover for Field K8.

Visual Estimations Versus Image Analysis of Percent Ground Cover for Field K8

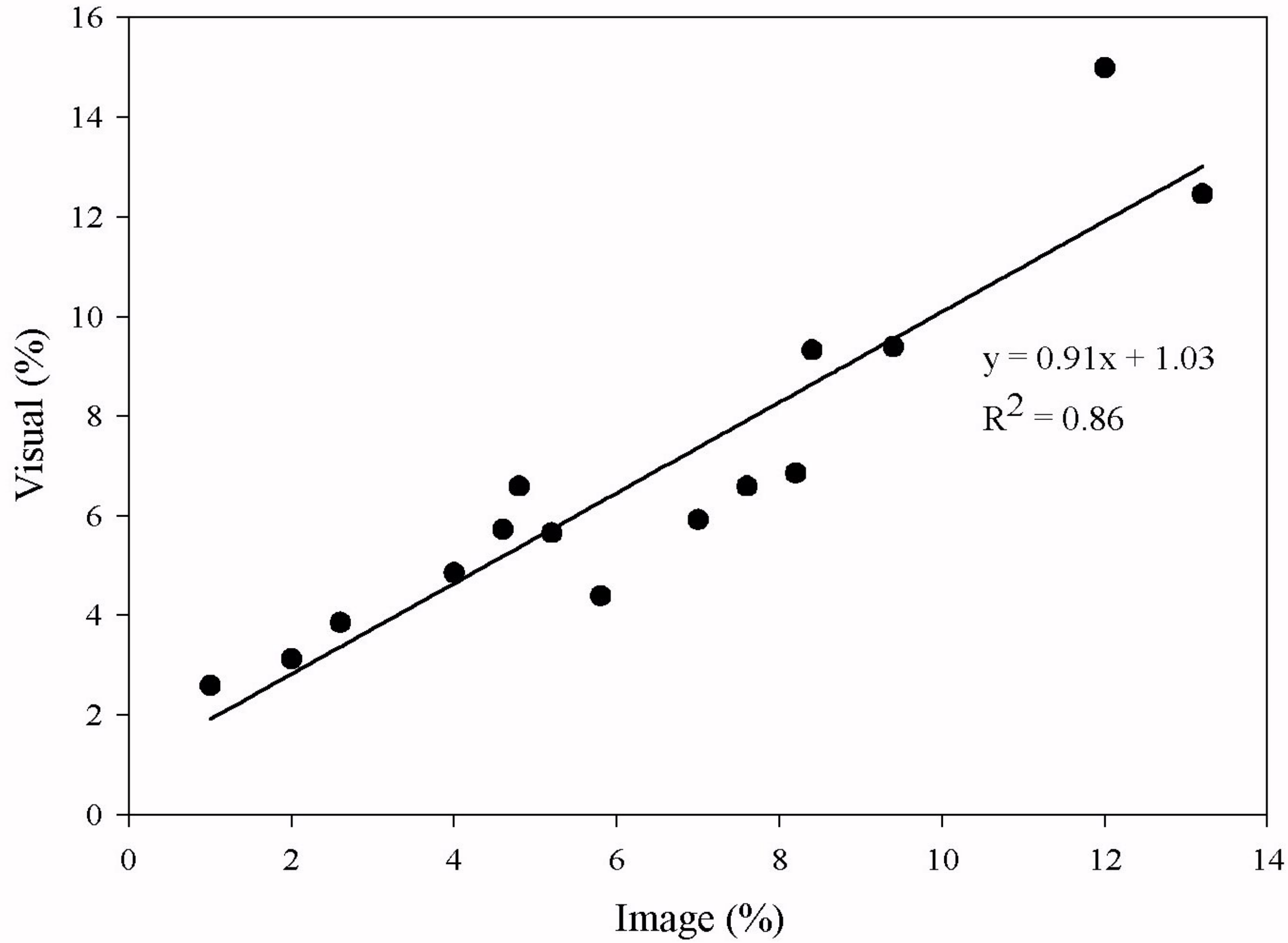


FIGURE LEGEND

FIGURE 6. Percent error of visual estimations as a function of percent ground cover for Field E4.

Percent Error Versus Percent Ground Cover for Field E4

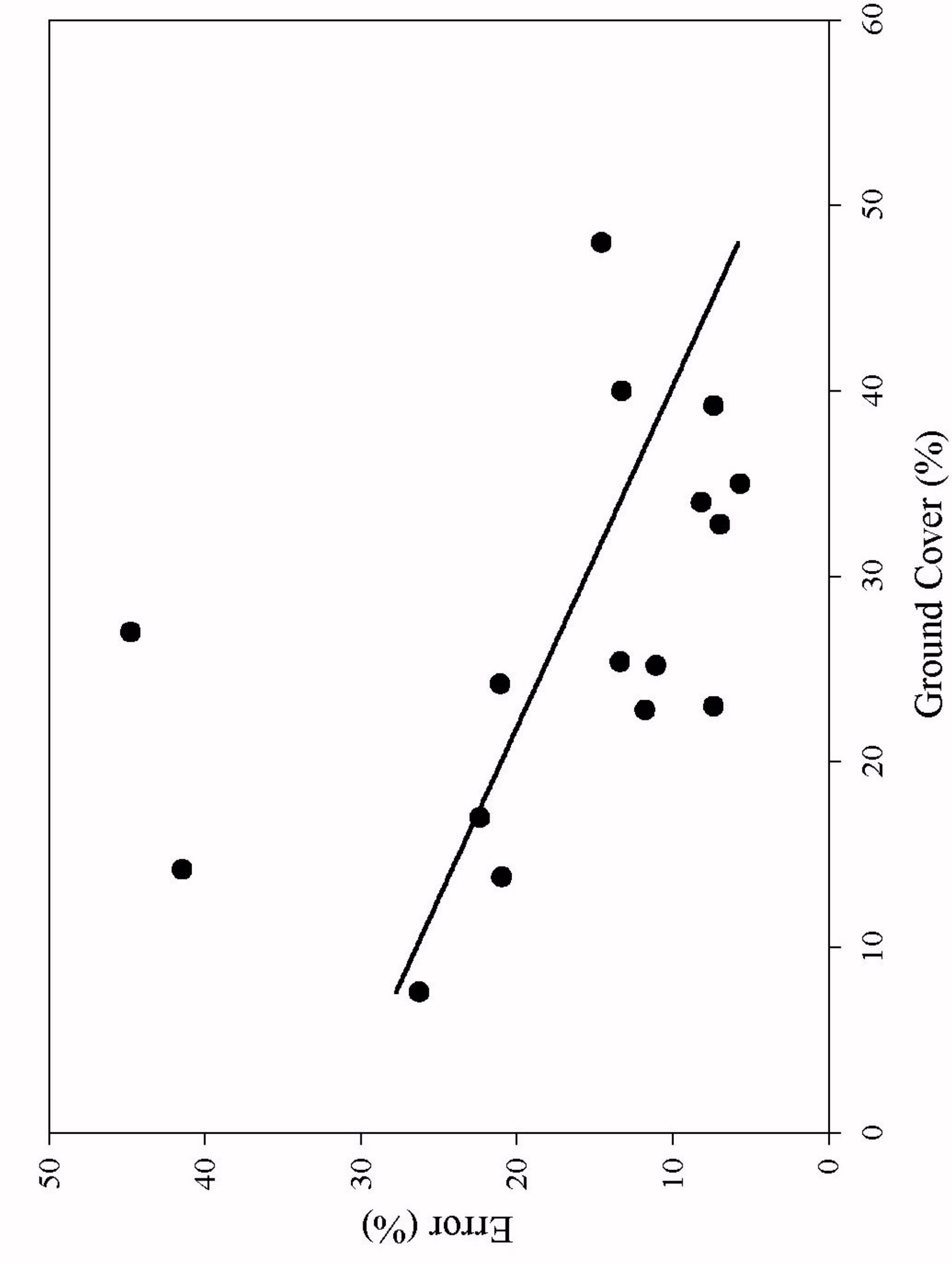


FIGURE LEGEND

FIGURE 7. Percent error of visual estimations plotted as a function of percent ground cover for Field K8.

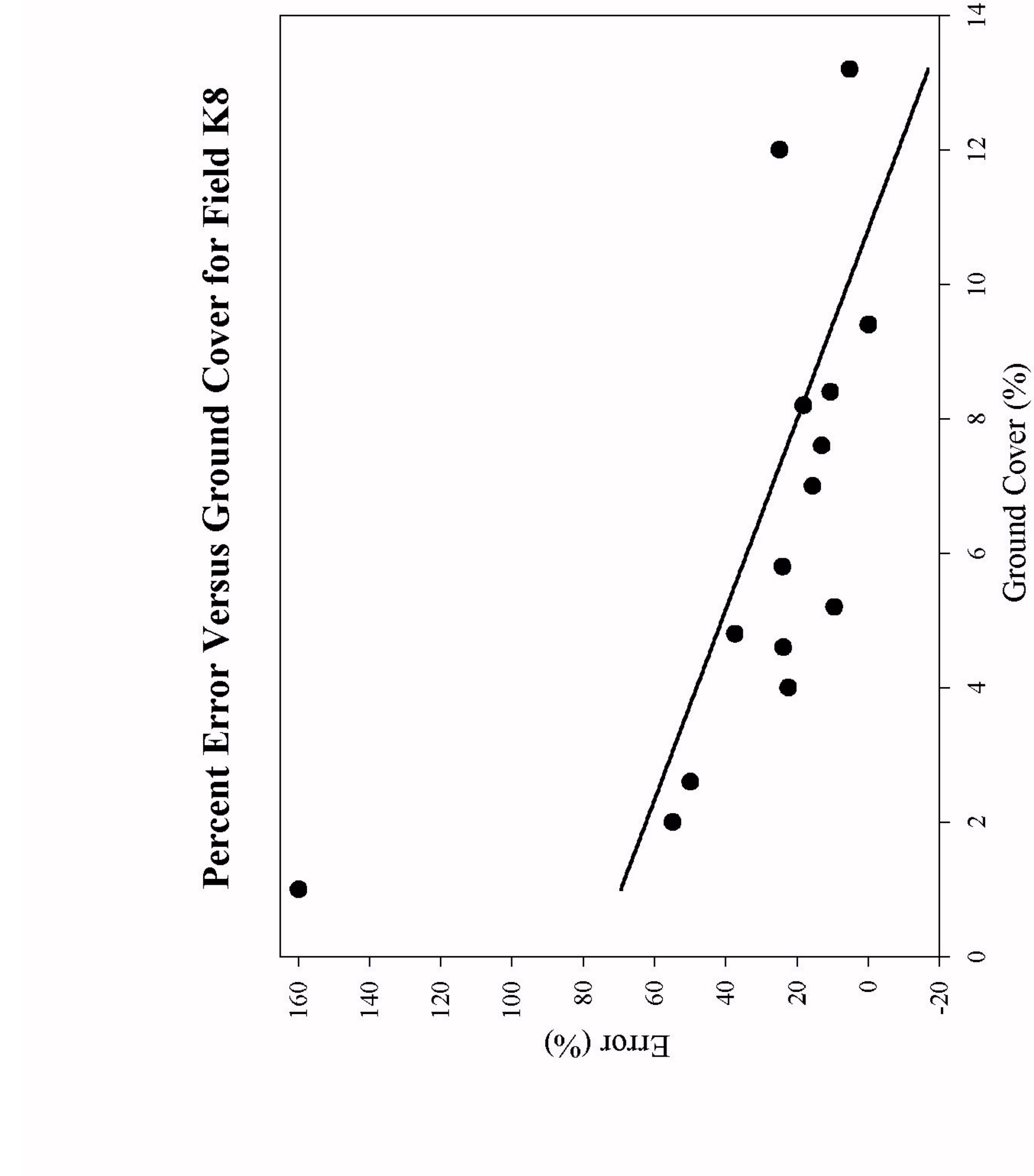
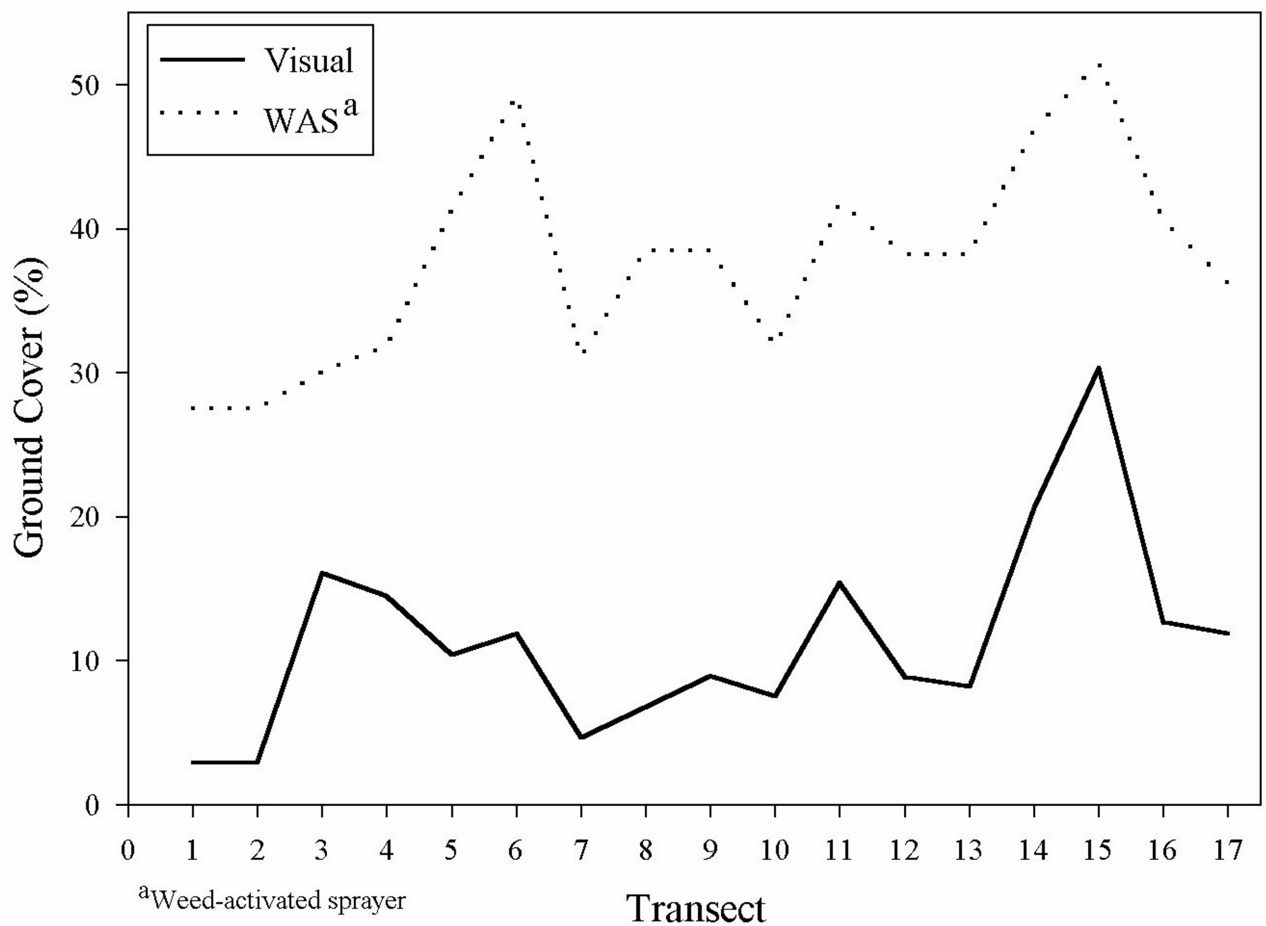

Percent Error Versus Ground Cover for Field K8
Error (%)
160
140
120
100
80
60
40
20
0
-20
Ground Cover (%)
0
2
4
6
8
10
12
14

FIGURE LEGEND

FIGURE 8. Mean of random visual estimates and non-random Weed-activated Sprayer measurements of percent ground cover plotted by transect for Field D1.

Random Visual Versus Non-random Weed Activated Sprayer Measurements of Percent Ground Cover for Field D1

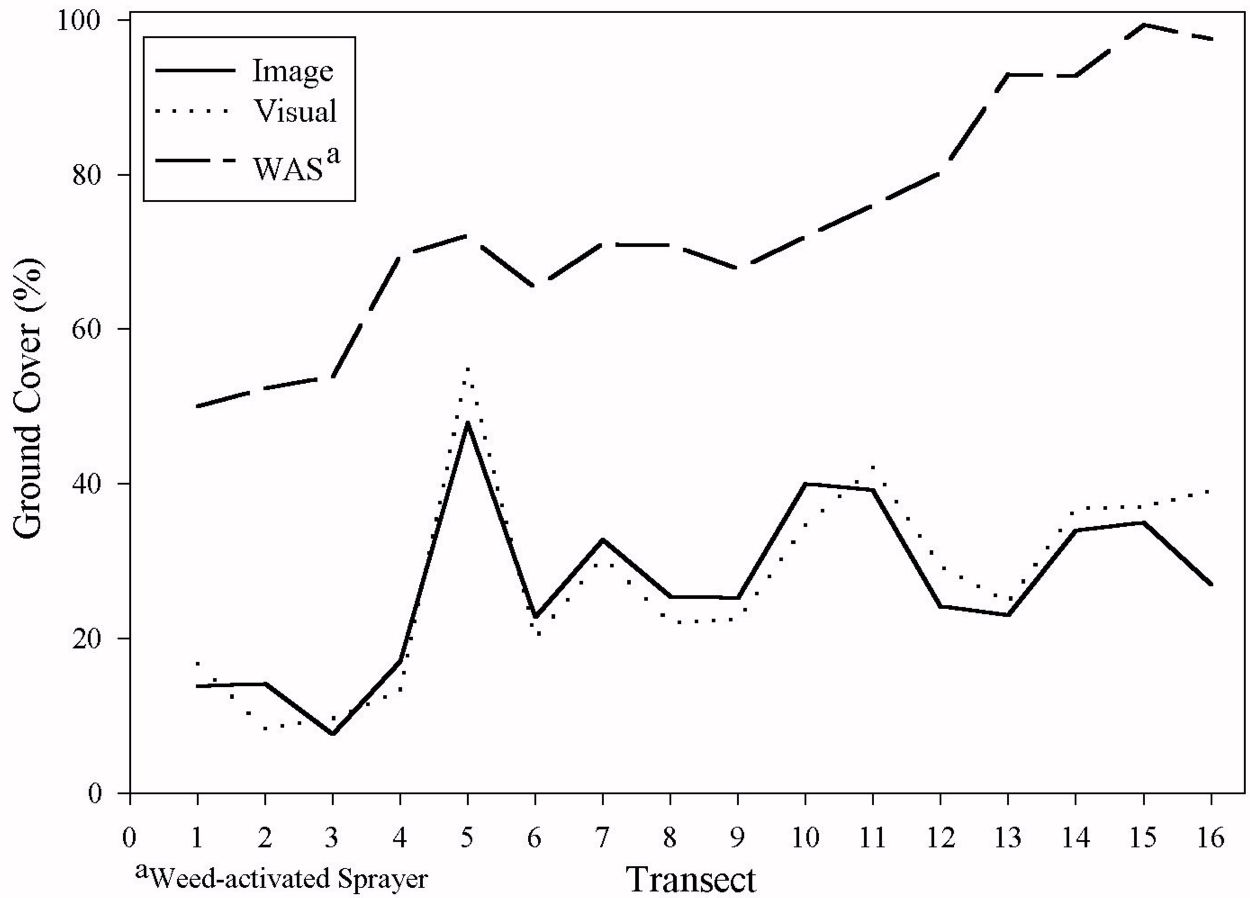


[a]Weed-activated sprayer

FIGURE LEGEND

FIGURE 9. Mean random visual estimates and non-random Weed-activated Sprayer measurements of percent ground cover plotted by transect for Field E4.

Random Visual and Image Analysis Versus Non-random Weed-activated Sprayer Measurements of Percent Ground Cover for Field E4

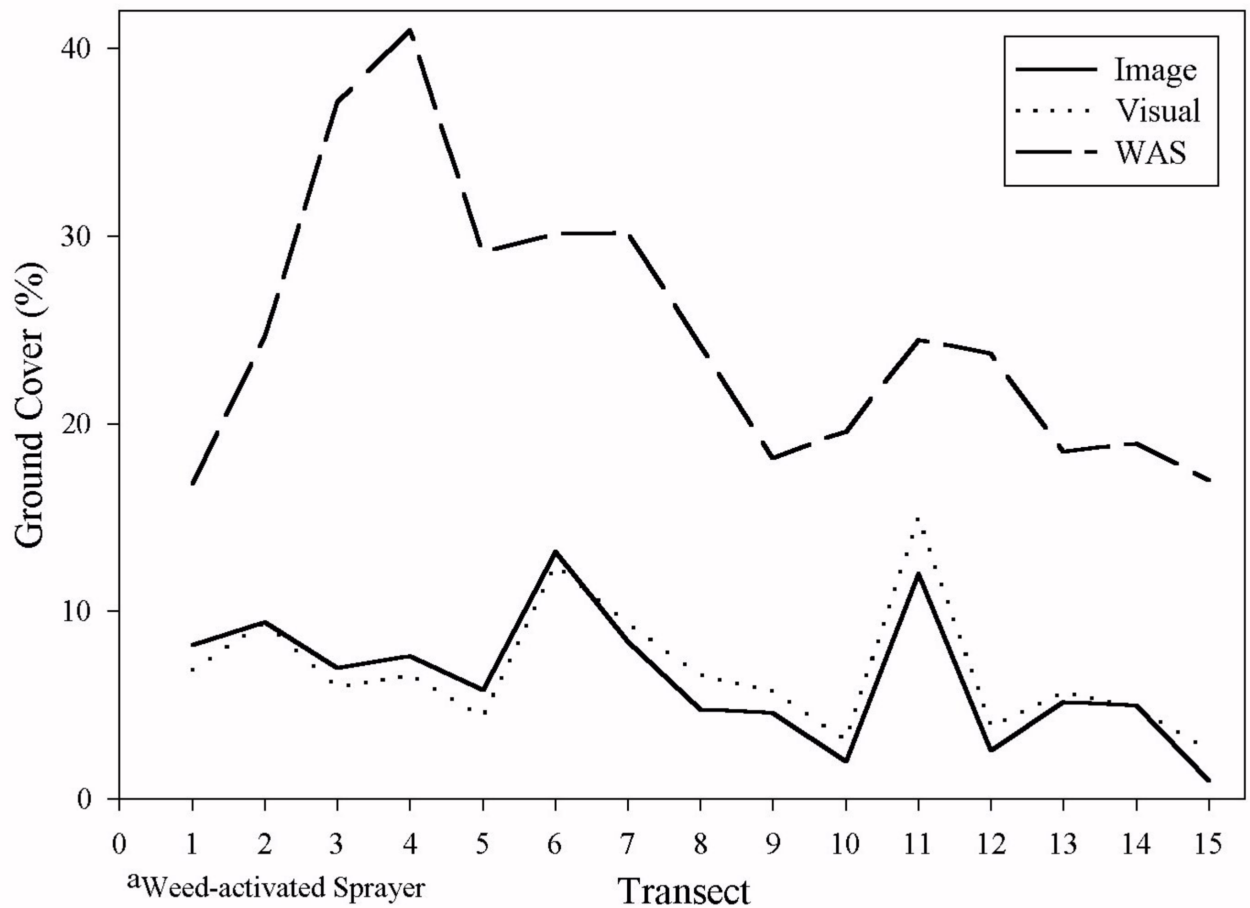


[a]Weed-activated Sprayer

FIGURE LEGEND

FIGURE 10. Mean random visual estimates and non-random Weed-activated Sprayer measurements of percent ground cover plotted by transect for Field K8.

Random Visual and Image Analysis versus Non-random Weed-activated Sprayer Measurements of Weed Ground Cover for Field K8

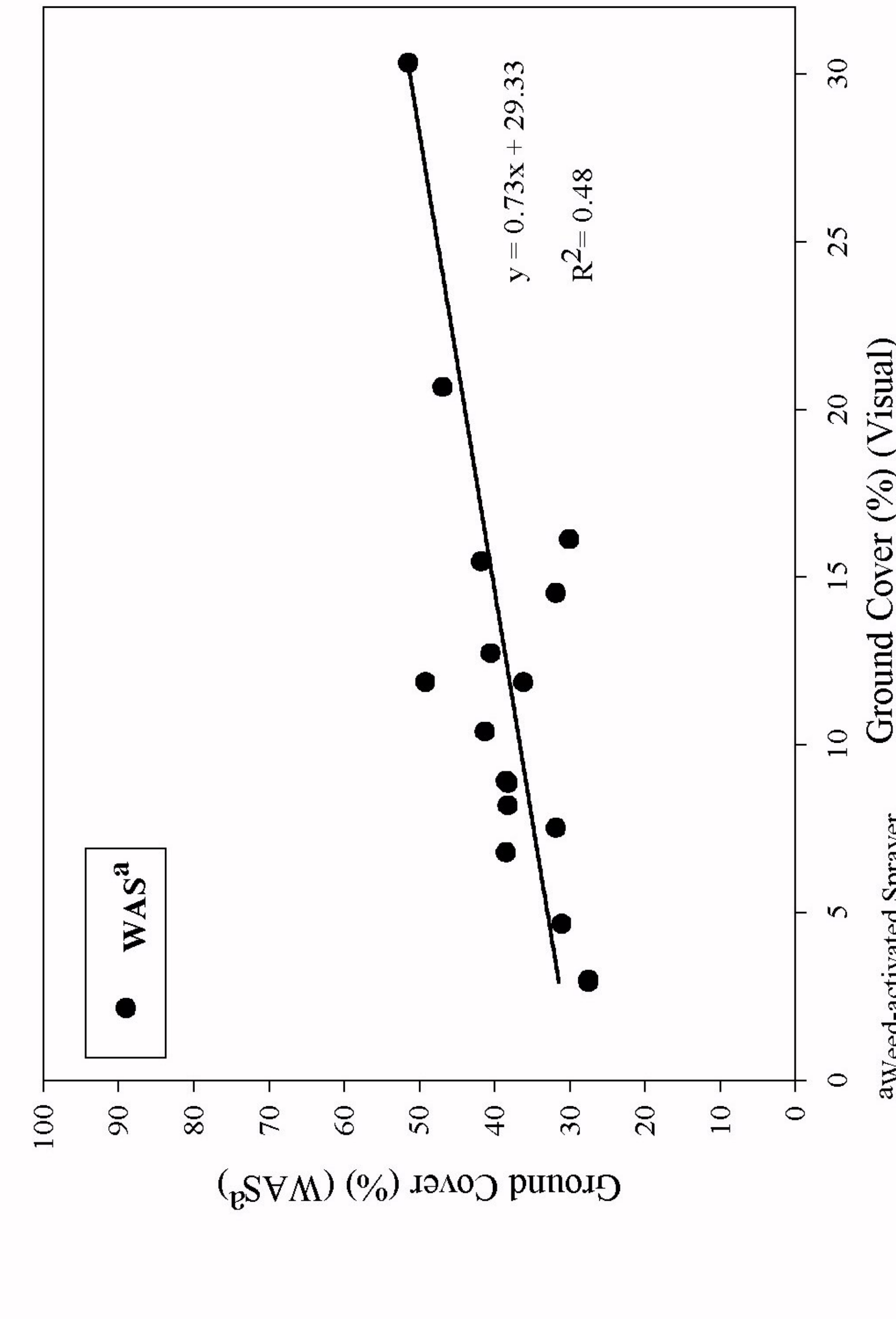


[a]Weed-activated Sprayer

FIGURE LEGEND

FIGURE 11. Weed-activated measurements of weed ground cover as a function of visual estimations of weed ground cover for Field D1.

Weed-activated Sprayer Measurements as a Function of Visual Estimations of Weed Ground Cover for Field D1

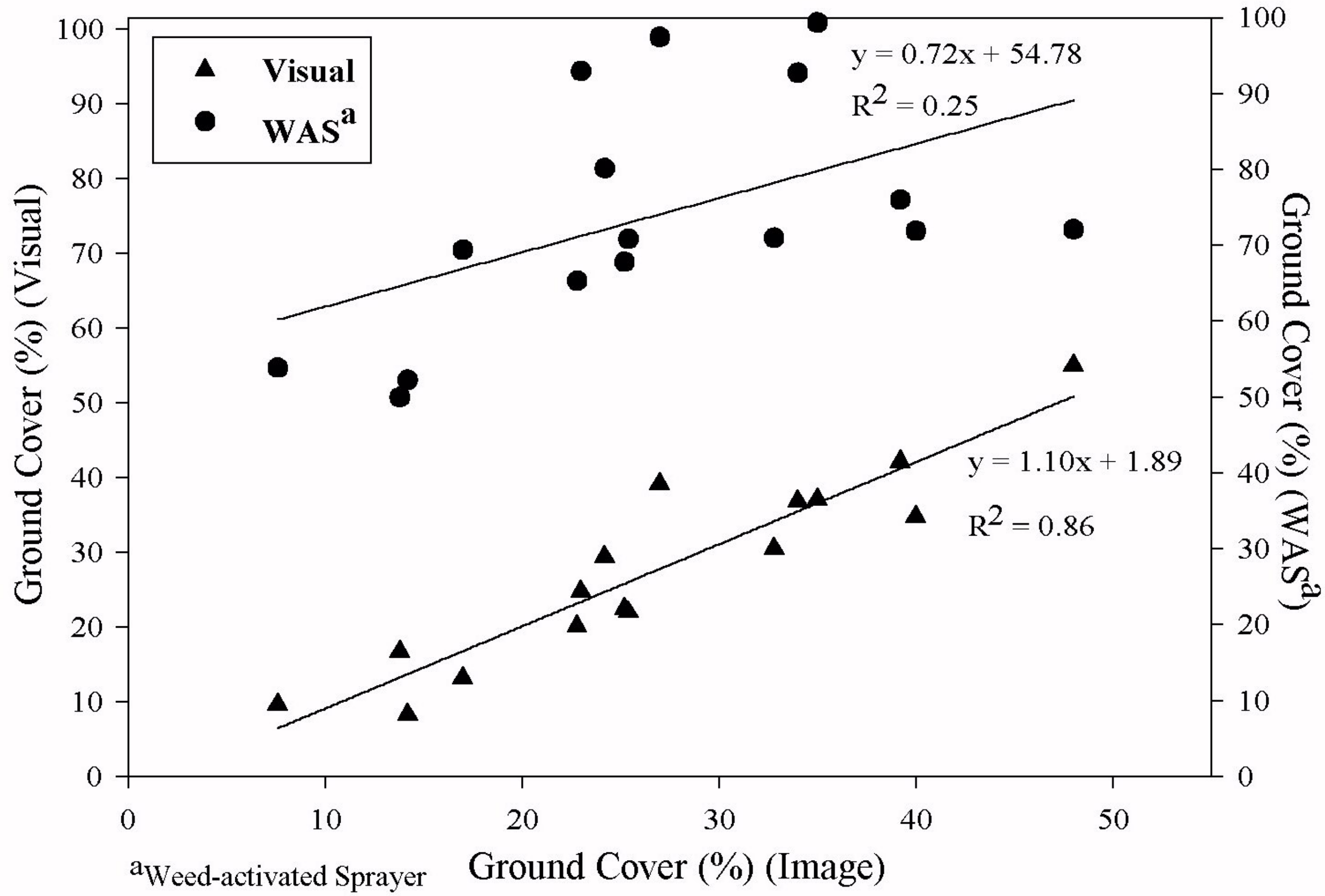


[a]Weed-activated Sprayer

FIGURE LEGEND

FIGURE 12. Weed-activated sprayer measurements and visual estimates of weed ground cover as a function of image analysis of weed ground cover for Field E4.

Weed-activated Sprayer and Visual Estimations of Weed Ground Cover as a Function of Image Analysis for Field E4

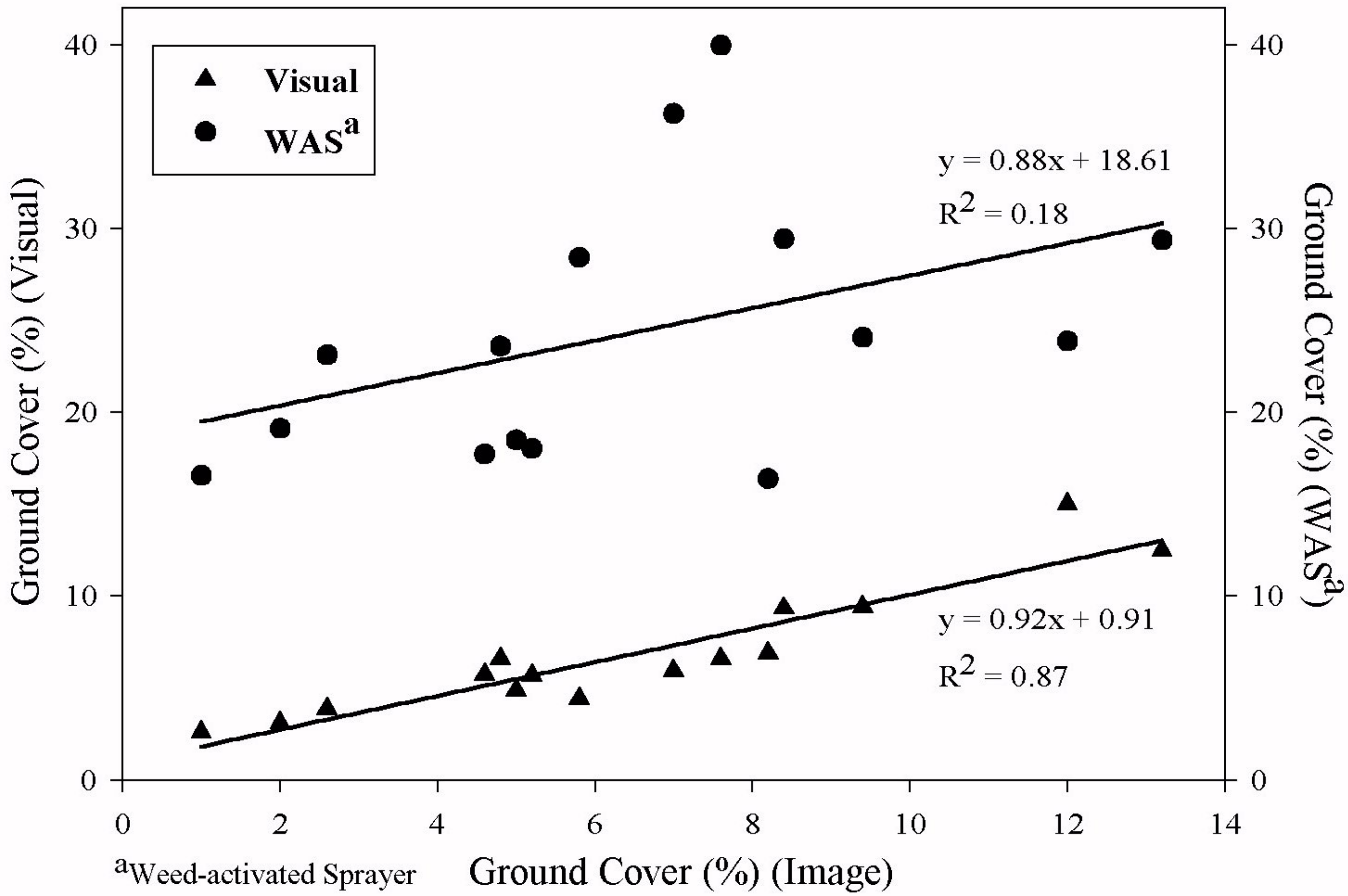


[a]Weed-activated Sprayer

FIGURE LEGEND

FIGURE 13. Weed-activated sprayer measurements and visual estimates of weed ground cover as a function of image analysis of weed ground cover for Field K8.

Weed-activated Sprayer and Visual Estimations of Weed Ground Cover as a Function of Image Analysis for Field K8



[a]Weed-activated Sprayer

FIGURE LEGEND

FIGURE 14. Plot of weed-activated sprayer measurements and visual estimations of percent ground cover that is normalized by subtracting the mean of all transects from each transect for field D1.

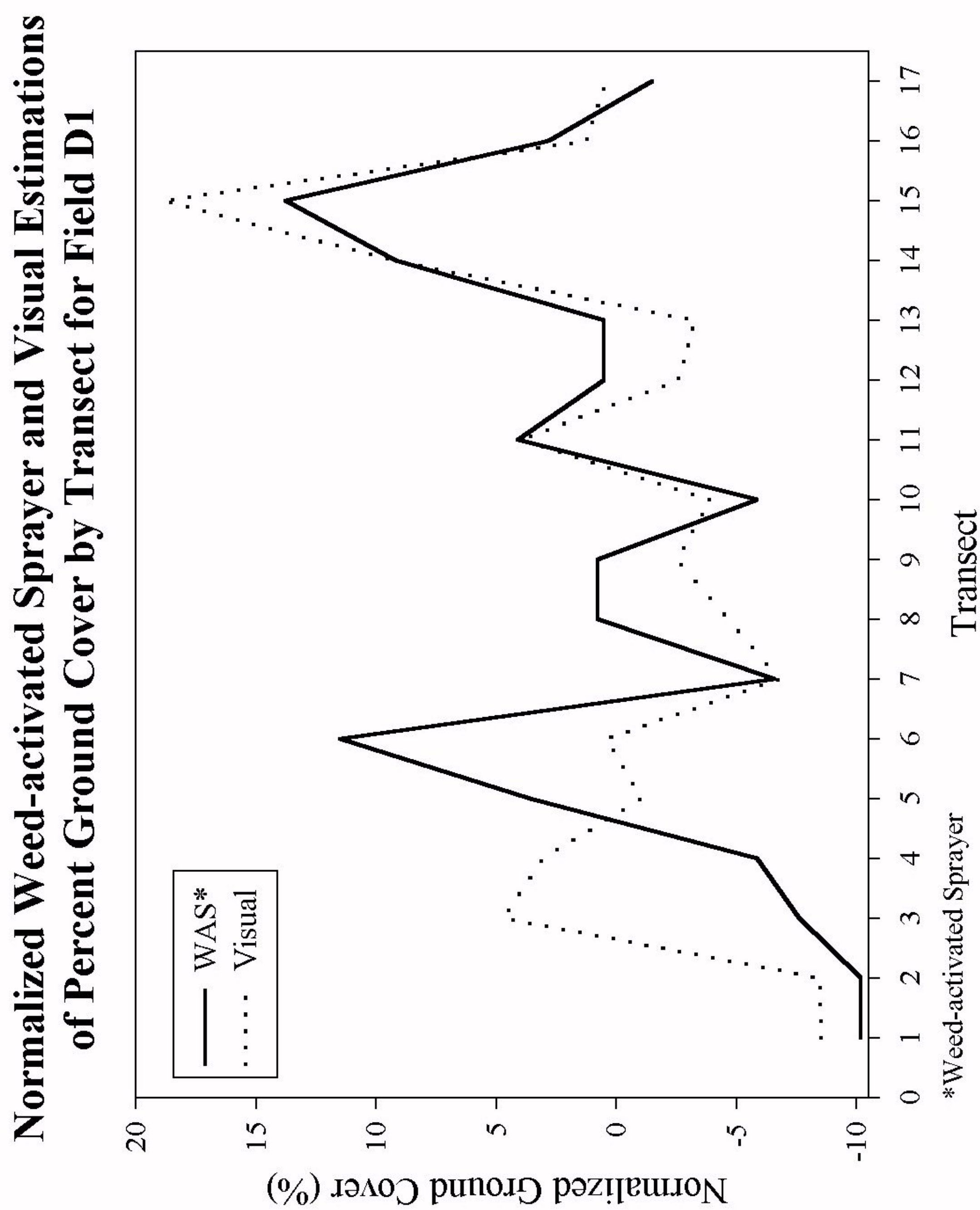
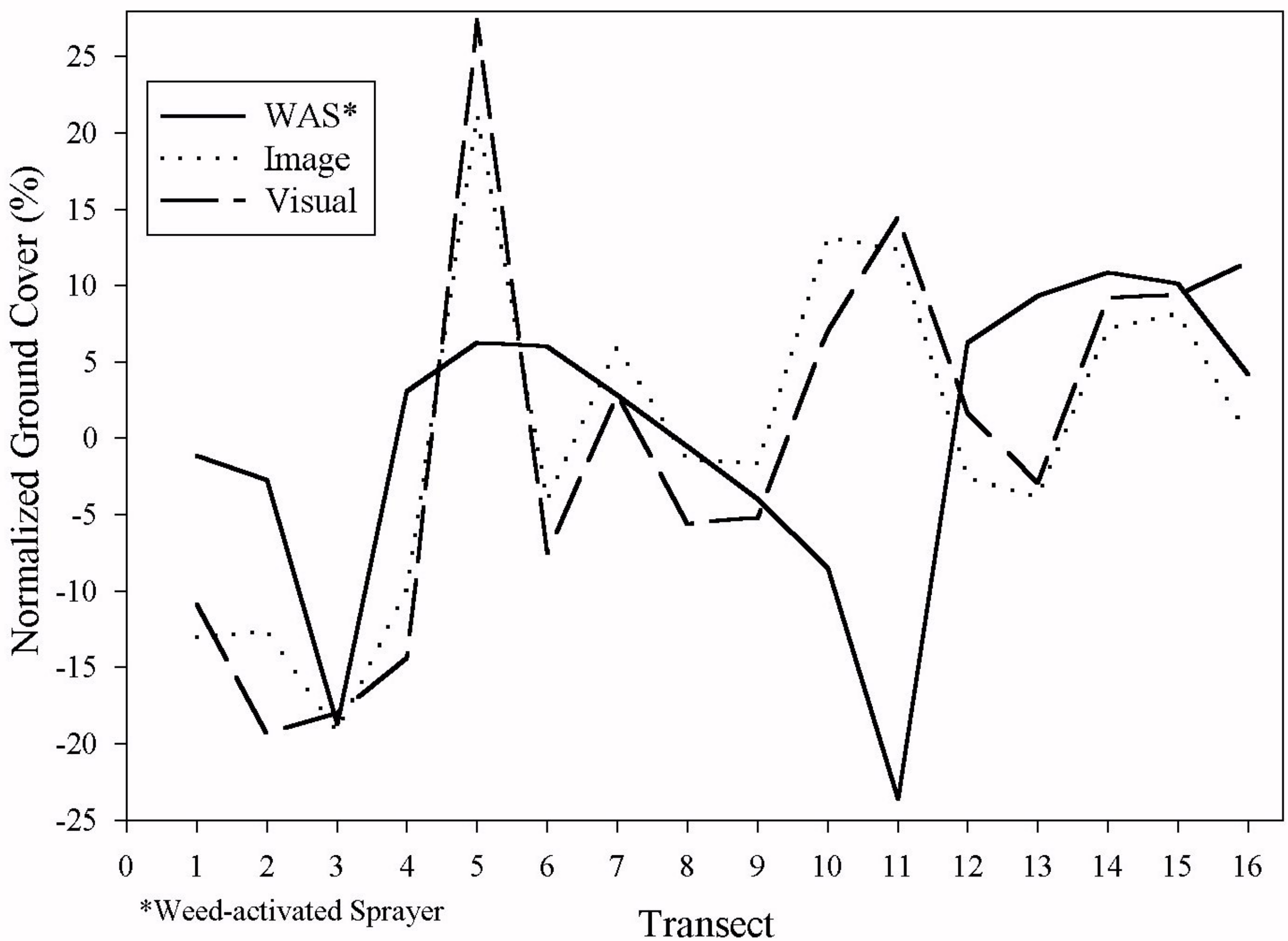

Normalized Weed-activated Sprayer and Visual Estimations
of Percent Ground Cover by Transect for Field D1
Normalized Ground Cover (%)
20
15
10
5
0
-5
-10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Transect
WAS*
Visual
*Weed-activated Sprayer

FIGURE LEGEND

FIGURE 15. Plot of weed-activated sprayer measurements, image and visual estimations of percent ground cover that is normalized by subtracting the mean of all transects from each transect for field E4.

Normalized Weed-activated Sprayer, Image and Visual Estimations of Percent Ground Cover by Transect for Field E4

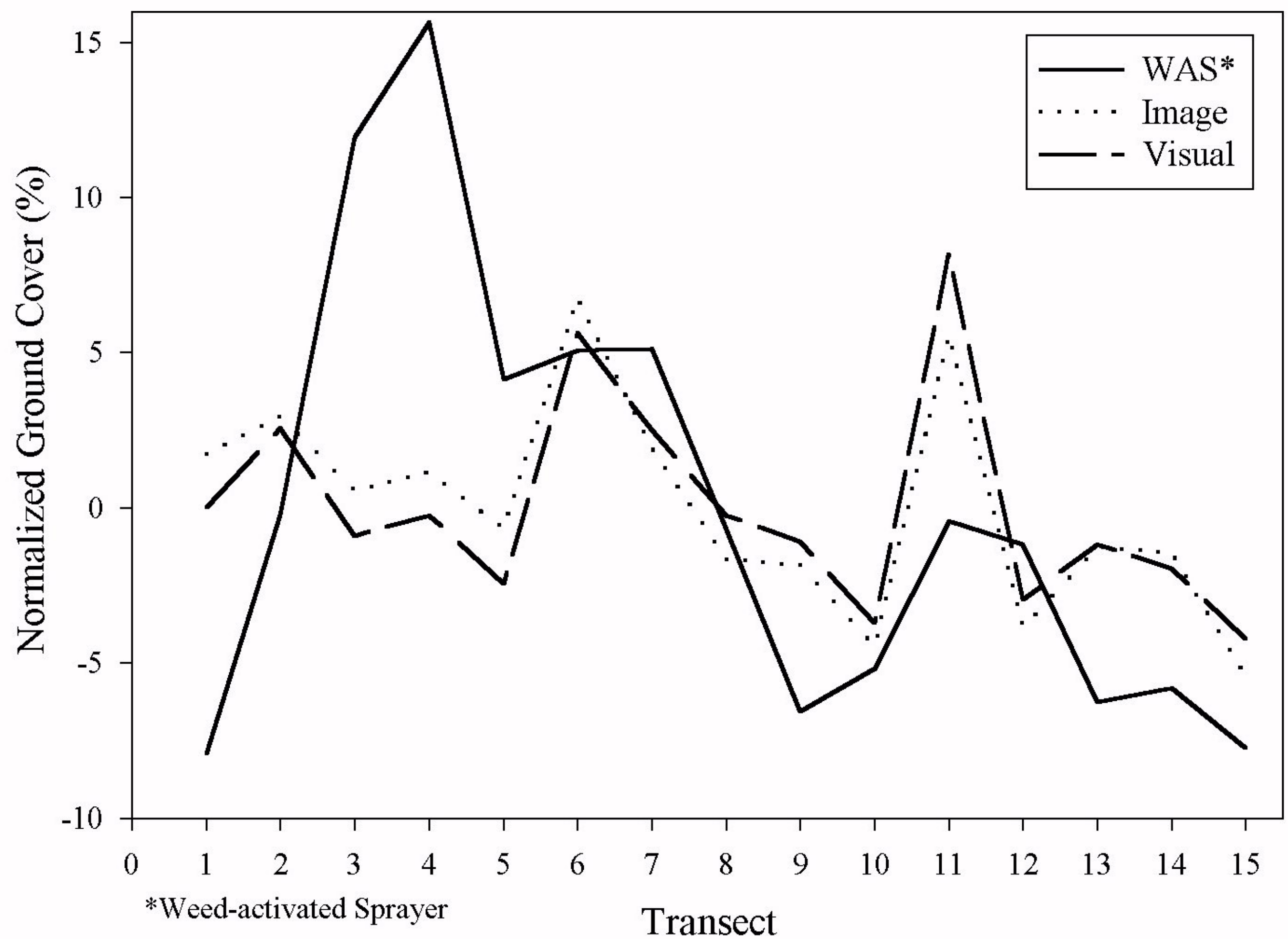


*Weed-activated Sprayer

FIGURE LEGEND

FIGURE 16. Plot of weed-activated sprayer measurements, image and visual estimations of percent ground cover that is normalized by subtracting the mean of all transects from each transect for field K8.

Normalized Weed-activated Sprayer, Image and Visual Estimations of Percent Ground Cover by Transect for Field K8



*Weed-activated Sprayer

SECTION IV.
DEVELOPMENT OF CALIBRATION SETTINGS FOR THE PATCHEN™ WEED-ACTIVATED SPRAYER[1]

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[1]W.J. Parks and D.C. Bridges. To be submitted to *Weed Technology*

ABSTRACT

Broadcast spraying of herbicides often results in over application of these herbicides, due to the spatial heterogeneity of weed distributions. Weed management strategies that take into account weed spatial distribution can include the use of weed-activated sprayers (WAS). Studies were conducted to determine the proper speed and sensitivity settings to be used for the Patchen™ WeedSeeker weed-activated sprayer in order to maximize target plant treatment while minimizing herbicide misapplication. Magnolia (*Magnolia grandiflora* L.) leaves were cut into six different weed sizes, and these were sprayed with dye on top of Plexiglas. Molena sand (94% sand, 4% silt, 2% clay) was used as a background matrix. The sprayer was operated at three speeds and five sensitivity settings. Digital images were taken of the sprayed areas and analyzed for the amount of leaf area sprayed (leaf spray), leaf area not sprayed (underspray), and overspray. Results showed that sprayer application failure was inversely proportional to weed size and sprayer sensitivity. Once the experimental design was refined, underspray was virtually nonexistent. As leaf area increased overspray decreased due to the fixed spray pattern. Predictive models based on available data showed that with a known weed size, one could adjust sensitivity and ground speed to maximize leaf spray. However, due to the fact that in the WAS design the sensor bandwidth and the solenoid latch time are fixed, there were no adjustable parameters that affected overspray. Ultimately a sensitivity setting of 2.5, and calibration on the darkest and wettest soil yielded the most accurate spray coverage and least overspray.

INTRODUCTION

In traditional cropping systems herbicides are applied as "broadcast" applications. Giles and Slaughter (1997) described broadcast spraying as the process of spraying the entire field "using a linear array of nozzles discharging individual overlapping patterns which combine to produce a single, uniform, continuous spray pattern." Rutherford (1985) described the wastefulness of broadcast pesticide application as "the least efficient industrial process on earth." These applications are wasteful because they do not take into account the location of the target plant, only the location of the crop plants, which are fixed and not variable. Since weeds generally exhibit a patchy distribution (Hofsten, 1947; Marshall, 1988; Thorton *et al*., 1990; Navas, 1991; Thompson *et al*., 1991; Mortensen *et al*., 1992; Stafford and Miller, 1993; Donald, 1994; Rew *et al*., 1996) broadcast spraying can lead to over application of herbicides (Hughes, 1989; Thorten *et al*., 1990).

A sprayer that takes into account the spatial variability of weed populations could be the answer to increasing herbicide use efficiency. In order to detect weeds, a sprayer has to distinguish the weed from the soil. In essence acting as a weed-activated sprayer (WAS). Distinguishing weeds from the background soil matrix has been accomplished (Haggar *et al*., 1983; Felton, 1990; Felton *et al*., 1991; Nitsch *et al*., 1991; Shearer and Jones, 1991; Hanks and Beck, 1998; Wicks *et al*., 1998) with varying degrees of success.

The theory of operation of weed-activated sprayers is that they use optoelectronic sensors to measure reflectance differences either between weeds and soil. Physical and chemical properties of plants and spectral properties of the emission source determine the reflectance characteristics of plants (Myneni and Ross, 1991). The emission source is usually the sun, but it can be an artificial source, such as the one used in the Patchen™ WeedSeeker (Hanks and Beck, 1998). There are three possible fates for light when a plant intercepts it: reflectance, absorptance, and transmittance (Hatfield and Pinter, 1993).

However, reflectance in distinct areas of the electromagnetic spectrum is the most commonly employed by weed-activated sprayers. Reflectance characteristics are also determined by the background matrix (i.e. soil) (Hoffer, 1978; Bauer, 1985). Soil reflectance is dependent on surface moisture, organic matter content, and soil particle size (Bowers and Hanks, 1964). Dry soils are more reflective than wet soils in the 320 to 1000 nanometer (nm) range (Cirpra *et al*., 1971; Condit, 1971) due to an apparent visual darkening of soil when it gets wet, which reduces reflectance in the visible spectrum (Planet, 1970). Stoner *et al*. (1980) pointed out that although similarly colored soils may exhibit similar reflectance characteristics in the visible spectrum, there are often significant differences in the near and middle infrared region of the spectrum. So, weed sensors that are activated by reflectance differences between soil and plants must take into account both the visible and the non-visible near-infrared (NIR) regions of the spectrum.

The theory of operation of the Patchen™ system is that in the photosynthetically active region (400 to 700 nm), plants have relatively low reflectance compared to soil, while in the near-infrared (NIR) region (700 to 1000 nm) plants have a significantly higher reflectance than soil (Jones, 1996). The optoelectronic sensors in the Patchen™ system take advantage of this difference in reflectance characteristics, allowing spray system control based on the presence or absence of a weed. Since soil type and weed size vary from field to field and within a single field, it is important to calibrate the Patchen™ system to the field conditions. Calibration of the system is also important in order to minimize overspray caused by the machine being set at too high a sensitivity. This study was conducted in order to understand what setting to use for the Patchen™ system based on weed size and tractor speed.

The objectives of this study were to determine the proper calibration settings of the Patchen™ WeedSeeker and the phantom overspray error. Phantom overspray error is the phenomenon that occurs when the sprayer activates in the absence of a weed (Hanks and Beck, 1998). For the purpose of this study, it also includes the over spray of smaller weeds due to the fixed width of the spray pattern, which is 22.86 cm.

MATERIALS AND METHODS

To accomplish these objectives, it was necessary to determine the background matrix and the proper plant material to be used in the experiment. Using a UniSpec Spectral Analysis System reflectance spectrometer (PP Systems, Haverhill, MA) to measure reflectance characteristics of various materials, an array of materials were analyzed to find reflectance characteristics similar to plants and soil encountered in the field. Reflectance measurements between 350 and 1150 nm were made of yellow, dark green and light green paper, green-painted fiberboard, a dull leaf plant (white clover, *Trifolium repens* L.), a shiny leaf plant (yellow anise, *Jasminum nudiflorum* L.), dark gray felt and a clay soil (Figure 1). The dark gray felt and the green-painted fiberboard appeared to be the closest to soil and actual plant material respectively. As mentioned earlier, in the 400 to 700 nm range plants have relatively low reflectance compared to soil, while in the 700 to 1000 nm range plants have a significantly higher reflectance than soil. The Patchen™ system uses one array of light emitting diodes (LED's) to provide red light at a peak of 660 nm with a 20 nm bandwidth. Another array of LED's provides near-infrared light by emitting at a peak of 770 nm with a 30 nm bandwidth. Further investigation revealed that while its reflectance at the 660 $\pm$ 20 nm area was similar to plant material, at the other relevant wavelengths (770 $\pm$ 30 nm) the green-painted fiberboard did not have the necessary reflectance characteristic to activate the Patchen™ spray system (Figure 2).

Although the gray felt did have the appropriate reflectance spectrum to serve as a background matrix, it was difficult to see the dye when it was sprayed on dark felt. The materials chosen were Molena sand (94% sand, 4% silt, 2% clay) as a background matrix and magnolia (*Magnolia grandiflora* L.) leaves as the plant material (Figure 3). Magnolia leaves were used because they had similar reflectance characteristics to most plants, and due to their waxy coating they provided a greater contrast between soil and plant. Magnolia leaves were also readily available, maintained their color for long periods of time, and were large enough to accommodate large weed sizes.

Using the Molena sand did not, however, alleviate the problem of not being able to see the dye when it was sprayed on it. To avoid this problem, a spray platform was constructed with a transparent spray surface on top. Grooves were cut (60.96 cm by 5.08 cm) into eight 2.54 cm by 10.16 cm by 4.88 m boards. Plywood was used to attach each board together at 1.22 meter intervals to provide support. Molena sand was filled in on top of the plywood to create a background matrix similar to one encountered in a field situation. Moderately thin Plexiglas (3.18 mm) was placed on top of the side pieces for a virtually transparent spray surface. Molena sand was also mounded up in between sample areas to provide support for the thin Plexiglas. Sample areas were spaced on 1.22 m centers with a 60.96 linear cm spray area allotted. The spray dye used was crystal violet (Fisher Scientific, Pittsburgh, Pennsylvania, CAS REG 548-62-9) at a rate of 25 g with 0.25% V/V surfactant mixed in 3 gallons of water.

Experimental design was a split, split plot. Dye was sprayed at three tractor speeds: two, three, and four miles per hour. Six different sizes of plant material (4, 25, 64, 121, 196, and 289 cm^2) were used to simulate weed sizes typically encountered in the field. Pseudo-weeds were created by cutting fiberboard into the appropriate size and then gluing the magnolia leaves onto the pieces and trimming the edges. Pseudo-weeds were made in the morning, and the test was conducted in the afternoon. The sensitivity setting on the Patchen™ WeedSeeker was varied between 1, 2.5, 5, 7.5, and 10 for each size and speed combination, and there were four replications of each combination. Only the center sensor in the center hood was used in the study.

After each spray pass an image was taken of the sprayed area using a Sony digital camera (Sony, Mavica) at a resolution of 1024 pixels by 768 pixels. Since the background matrix is very dark and the dye would be difficult to see, a white painted board was inserted in the groves of the sideboards underneath the Plexiglas. This allowed the spray pattern to be viewed against a white background. This process was repeated for all combinations of speed, size and sensitivity.

Once all images were captured, they were analyzed to determine leaf area sprayed, leaf area not sprayed and over spray (Beverly, 1996). Once the images were loaded onto a personal computer (PC), each image was cropped to just the frame itself using the computer software Paint Shop Pro (Paint Shop Pro, JASC Inc., Eden Prairie, Minnesota). The image analysis was performed using the SigmaScan Pro software (SigmaScan Pro, SPSS Inc.; Chicago, Illinois).

Selecting the part of the weed that was sprayed with the spray dye, and then determining the area of this selection using the area measurement function in the software found the leaf area sprayed. Defining the area by the color of the dye and then using the area measurement function of the software found the amount of over spray. Then the leaf area sprayed was subtracted from the over spray area to get the actual area of over spray. To calculate the area of under spray, the leaf area sprayed was subtracted from the total leaf area of the weed.

Using SAS (SAS, 1987), data were analyzed using a response surface regression and multiple regression to determine the parameters to be used in the individual models. After determining significant parameters, a regression analysis was performed for each variable along with the significant interactions and higher order terms. In order to select the proper polynomial model the Type I (sequential) sum of squares were divided by the mean square error and these values were compared to the appropriate F-statistic to determine significance. The final model was constructed from the sequential β estimates.

RESULTS AND DISCUSSION

Several variables were measured to characterize system performance. When a target weed is sensed and the WAS is activated four potential outcomes are possible. First, theoretically the target can be sprayed perfectly, that is no overspray and no underspray occurs. Although this is the ideal situation, it never occurs. A second outcome is that phantom overspray occurs, which means area in excess of the actual target area is sprayed, resulting in wasted herbicide. Overspray should be minimized with proper instrument design and setup. The third outcome is to fail to spray all of the target area, which results in poor weed control, and is referred to as underspray. The final possible outcome is for the WAS to fail to recognize the target entirely, resulting in lack of activation. In this case no spray is deposited on the target or the nontarget area.

Overall system performance. <u>WAS activation</u>. Operationally, slight overspray is the preferred outcome compared to underspray or failure to activate. However, failure to activate was a common problem in these tests and was well correlated with several operational settings. Activation failure of the Patchen™ system was inversely proportional to the size of the target weed (Figures 7, 8, and 9). The 4-cm^2 pseudo-weeds were just too small to activate the sensor. However, it is important to note that the Patchen™ is designed with three sensors per hood allowing for some redundancy in sensing. In these experiments because targets were perfectly aligned directly beneath the center sensor in each hood, only one sensor monitored the target zone and controlled spraying. It is possible that with the redundancy of three sensors, some targeting failures may be overcome. Also, activation failure increased as the sensitivity setting on the system was decreased. Sensitivity settings on the Patchen™ range from 1 to 10, with 1 being the most sensitive setting. The manufacturer routinely suggests a setting of 2.5. Relative to activation failure rate, a setting of 2.5 appears to be the proper setting, but it was not exact for all weed size and speed combinations (Figures 7, 8, and 9). Speed did not consistently affect system failure rate. As will be described later, system performance was inconsistent at 2 mph (speed 1). System failure rates were very similar at speed settings two and three for weed sizes three and larger. With small weeds, size 1 and 2, failure rate was much higher across all speeds.

Underspray. Failing to sense the presence of the target or slow response time can lead to the target being sprayed incompletely (the condition of underspray). At 2 mph, underspray ranged from less than 5 percent to approximately 70 percent and was very inconsistent. In contrast, underspray was almost nonexistent at 3 and 4 mph (Figures 5 and 6), typically much less than ten percent.

Somewhat unpredictable system performance resulted in significant variation in all parameters measured at speed one, primarily because experimental conditions were inconsistent with respect to soil reflectance and sensitivity setting. The soil reflectance was not consistent across the entire plot area because of varying soil moisture contents, which causes differences in reflectance characteristics. The variability in moisture content resulted in improper sensing and activation timing in the Patchen™ system. This problem was corrected in subsequent tests by misting a small amount of water onto the entire area before testing began. Also the Patchen™ system was calibrated differently with this first speed than with the other two speeds. With the first speed, the system was calibrated on soil that was in the mounded part of the test area. This was an area of lighter color and was thus more reflective than darker regions of the test area. With speeds two and three, the Patchen™ system was calibrated on the darkest part of the test run, and this resulted in better system performance. This leads to the conclusion that for use in field situations, the Patchen™ system should be calibrated on the darkest and most moist (thus least reflective) soil type found in the spray area.

Overspray. As leaf size increased, percent overspray decreased (Figures 4, 5, and 6). With a fixed-width spray pattern and a fixed spray solenoid latch and release time one would expect an overspray area, as a percentage of target area, to decline as target size increased. For weed sizes of three and larger, overspray ranged from about 15 to 40% and. Instrument sensitivity setting had little effect on overspray.

Models to optimize performance. Optimizing performance, that is maximizing the amount of target area that is sprayed correctly (leaf spray) while minimizing spray activation failure, overspray, and underspray, requires knowledge of target weed size, which in turn can be used to set instrument sensitivity and operational speed. Regression analysis, using response surface regression and multiple regression, was used to develop models to predict leaf spray, overspray, and underspray.

Initially response surface regression was used to determine the effect of sensitivity setting, speed, and weed size on the variables that were measured. Later multiple regression, using the GLM procedure of SAS, was used to determine the effect of first and second order and cross-product terms of speed, size, and sensitivity. The percentage variables were created in order to be able to compare overspray and underspray on a common scale. Terms for the final model were selected using Type I sums of squares and parameters were taken from sequential ß estimates.

Leaf Spray. The amount of leaf area that was sprayed correctly was influenced by speed, sensitivity, and weed size (Table 2). A final model was selected that included these terms and a second order term for size and sensitivity: $y = 3.95 + 6.18\ (\text{Speed}) - 11.42\ (\text{Size}) + 9.48\ (\text{Size}^2) - 3.52\ (\text{Sensitivity}) + 0.29\ (\text{Sensitivity}^2)$. Using this equation to predict leaf spray resulted in values that compared very well with observed values (Figure 10), having a slope of nearly 1.0 (0.99) and a y-intercept of -2.9. Review of parameter estimates for the final model for leaf spray indicates that with known, or fixed weed size, which can be determined on site-specific basis, one can easily adjust sensitivity and ground speed to achieve a high level of spray coverage. In fact, adjustments in sensitivity had little effect on leaf spray assuming one was in the mid-range of sensitivity adjust, i.e. 2.5 to 5.0.

Percent spray. Predictive equations for the percent of the target that was sprayed correctly were much less useful, primarily because weed size is the most powerful parameter within the model. Hence, dividing leaf areas sprayed by the total leaf area effectively removed this powerful parameter from the model, leaving only speed and sensitivity to account for effect, and resulting in parameter estimates that were less meaningful and reducing the R^2 to only 0.19.

Overspray. Overspray was very strongly affected by weed size, as is evidenced by the magnitude of the parameter estimate (140.68), which is more than 100 times that of other parameters within the final model. The final model was: y = 498.37 + 140.68 (Size) - 9.06 (Size^2) - 8.02 (Sensitivity) - 0.80 (Sensitivity^2). So, as weed size increased, the proportion of time the sprayer was activated increased, resulting in increased overspray. This occurred because the application bandwidth and nozzle solenoid latch and release times are fixed. The effect of these fixed components is reflected in the y-intercept value of 498.

Percent overspray. Percent overspray was calculated by dividing overspray area by the weed size, or total target area. This was done to allow direct comparison of overspray effects across weed, or target, size. Doing so resulted in reversing the sign of the parameter estimate for size from positive to negative, but the magnitude of the parameter remained large, indicating that even where adjustments are made for target size that this parameter remains highly influential. An important feature of this part of the analysis is that even though total overspray increased with increasing target size, the error, or percentage overspray relative to target size, decreased with increasing target size. Final models for both overspray and percent overspray indicated that a significant portion of overspray, or phantom spray, error is associated with fixed elements of the design. Overspray is unavoidable as long as these features remain a part of the system.

Underspray. Underspray was virtually nonexistent at 3 and 4 mph. Failure to spray target area appeared to be a very random process, unaffected by sensitivity or size, once size was above a critical minimum. Once a critical minimum weed size was achieved speed and sensitivity weakly affected underspray area, but these affects were not well correlated with failure to achieve complete coverage of the target. Transforming data to percent underspray did not provide a clearer understanding of the effects of weed size, speed, or sensitivity on underspray.

Proper calibration of the Patchen™ system is vital to maintain system performance. Clearly, weed size is a major factor in determining system performance. However, from an operational standpoint weed size is usually fixed. In other words, for a particular site weed size, effects are limited by the size of the smallest target weeds. In this experiment, which utilized only one of the three sensors per hood, weeds needed to be larger than 4-cm^2, otherwise unacceptable activation failures occurred. It appears that once a critical minimum weed size is achieved, size becomes an important determinant in overspray, or phantom spray conditions. If the instrument sensitivity was set within the guidelines provided by the manufacturer, small changes in sensitivity had little effect on the performance of the sprayer.

Not only does weed size and tractor speed affect machine operation, but soil type and soil moisture content does also. Background instrument calibration relative to soil reflectance is critical to proper operation of the Patchen™ system. The system should be calibrated on the least reflective soil surface, i.e. darkest soil type with the highest moisture content, to insure proper operation.

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Table 1. Parameter determination for each model

Model	Speed	Size	Sensitivity	Size x Speed	Speed x Sensitivity	Size x Sensitivity	Size x Speed x Sensitivity	R^2
Leaf Spray	0.0017*	0.0001*	0.0654	0.4126	0.0001*	0.4940	0.5059	0.98
Under Spray	0.0017*	0.5102	0.0654	0.4126	0.0001*	0.4940	0.5059	0.55
Over Spray	0.8568	0.0070*	0.0017*	0.4628	0.0953	0.9938	0.9470	0.46
Percent Spray	0.0001*	0.0001*	0.0001*	0.3158	0.0001*	0.0001*	0.2591	0.70
Percent Under	0.0001*	0.0001*	0.0001*	0.3158	0.0001*	0.0001*	0.2591	0.71
Percent Over	0.0870	0.0001*	0.0001*	0.0498*	0.2392	0.0001*	0.5541	0.98

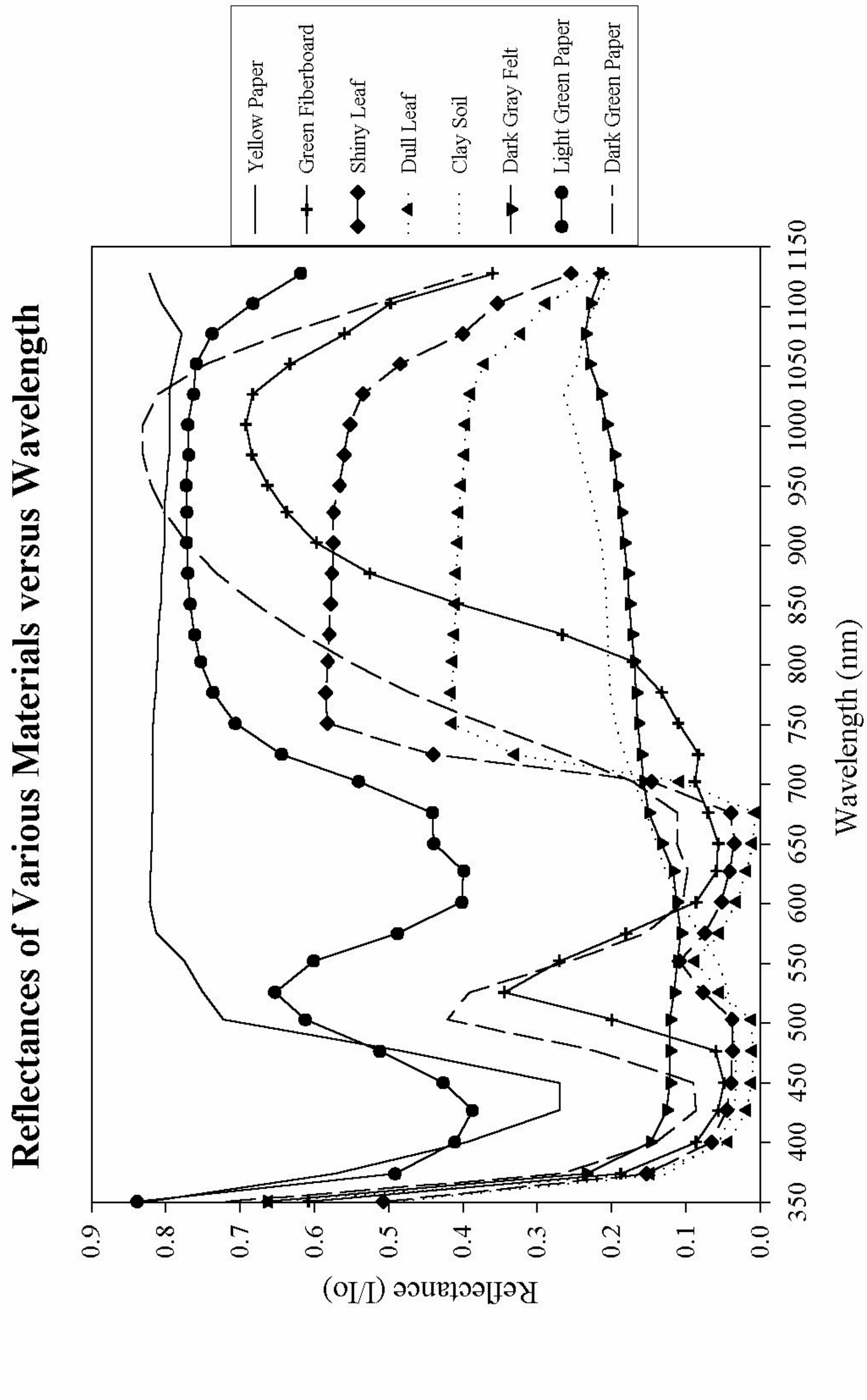
* Terms marked were included in the model along with higher order and base terms

Table 2. Parameter coefficients for each model.

Model	Leaf Spray	Under Spray	Over Spray	Percent Spray	Percent Under	Percent Over
Intercept	3.95	9.52	498.37	0.74	0.26	136.74
Speed	6.18	-5.92	N/S*	0.20	-0.20	-10.61
$Speed^2$	N/S*	N/S*	N/S*	-0.04	0.04	N/S*
Size	-11.42	N/S*	140.68	0.01	-0.01	-49.33
$Size^2$	9.48	N/S*	-9.06	N/S*	N/S*	4.42
Sensitivity	-3.52	3.67	-8.02	-0.03	0.03	-1.72
$Sensitivity^2$	0.29	-0.29	-0.80	0.01	-0.01	N/S*
Speed x Size	N/S*	N/S*	N/S*	N/S*	N/S*	2.17
Speed x Sensitivity	N/S*	N/S*	N/S*	N/S*	N/S*	N/S*
Size x Sensitivity	N/S*	N/S*	N/S*	N/S*	N/S*	0.33
Speed x Size x Sensitivity	N/S*	N/S*	N/S*	N/S*	N/S*	N/S*
R^2	0.97	0.11	0.13	0.19	0.19	0.66

* Terms marked were not significant and thus not included in the final model.

FIGURE 1. Reflectance ratios of green-painted fiberboard, dull leaf (*Trifolium repens*), shiny leaf (yellow anise), clay soil, dark gray felt, light green, dark green and yellow paper plotted versus wavelength.



Reflectances of Various Materials versus Wavelength
Reflectance (I/Io)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Wavelength (nm)
350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050 1100 1150
Yellow Paper
Green Fiberboard
Shiny Leaf
Dull Leaf
Clay Soil
Dark Gray Felt
Light Green Paper
Dark Green Paper

FIGURE LEGEND

FIGURE 2. Reflectance ratios of green-painted fiberboard, *Trifolium repens*, clay soil and dark gray felt with red and infrared LED peaks and bandwidths designated plotted versus wavelength.

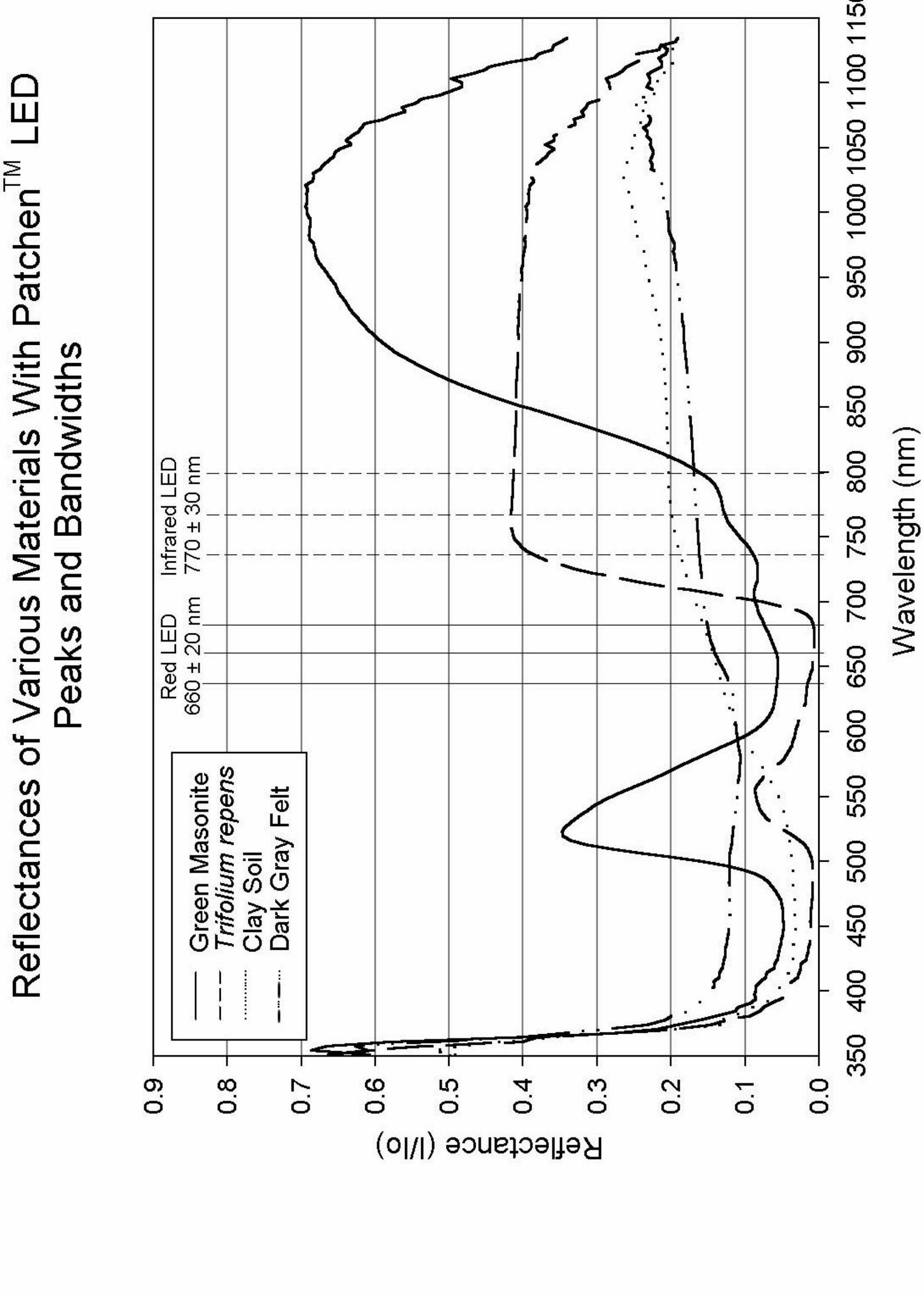

Reflectances of Various Materials With Patchen™ LED Peaks and Bandwidths
Green Masonite
Trifolium repens
Clay Soil
Dark Gray Felt
Red LED 660 ± 20 nm
Infrared LED 770 ± 30 nm
Reflectance (I/Io)
Wavelength (nm)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150

FIGURE LEGEND

FIGURE 3. Reflectance ratios of *Magnolia grandiflora*, *Trifolium repens*, clay soil and Molena sand with red and infrared LED peaks and bandwidths designated plotted versus wavelength.

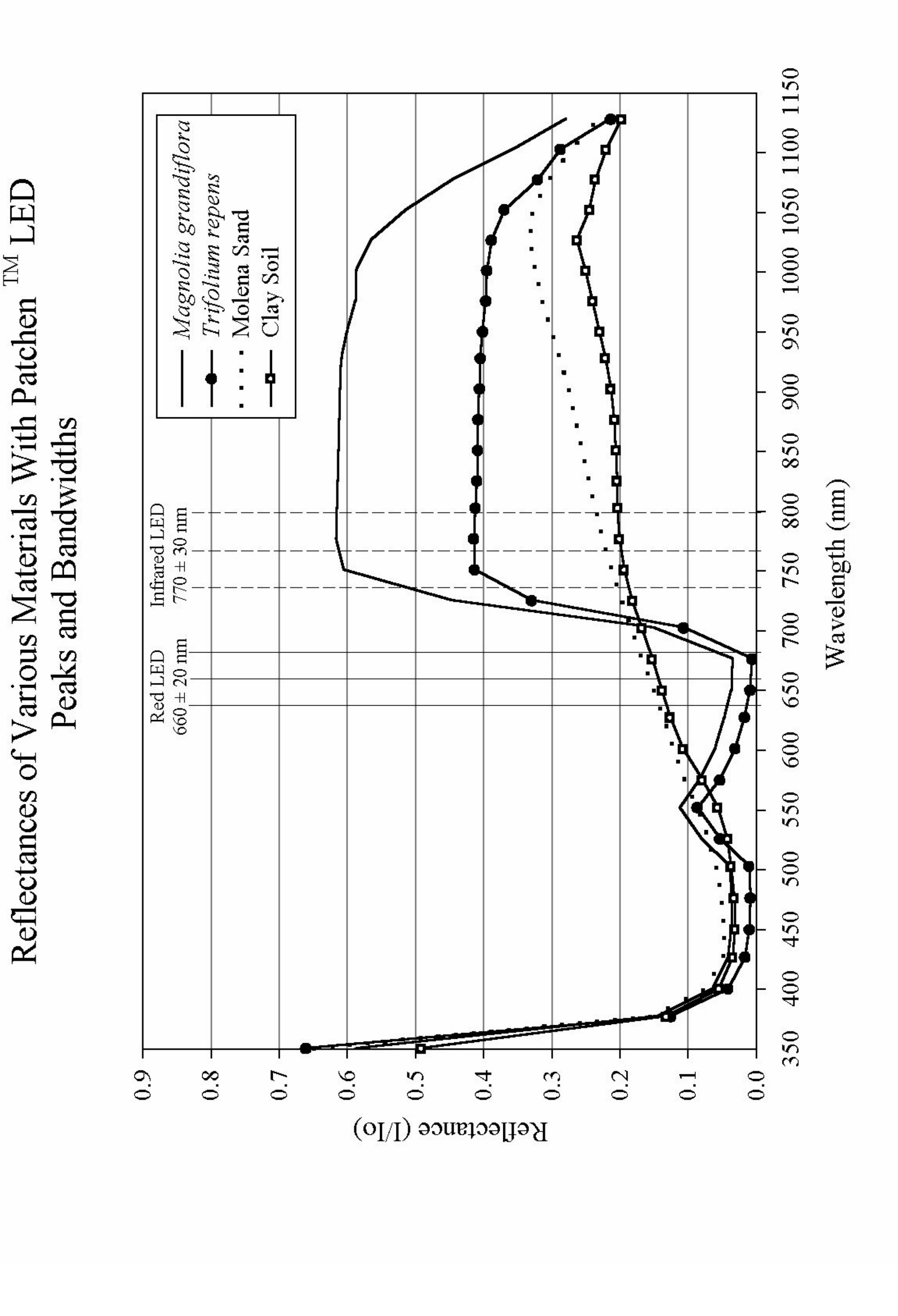

Reflectances of Various Materials With Patchen TM LED
Peaks and Bandwidths
Magnolia grandiflora
Trifolium repens
Molena Sand
Clay Soil
Red LED
660 ± 20 nm
Infrared LED
770 ± 30 nm
Reflectance (I/Io)
Wavelength (nm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150

FIGURE LEGEND

FIGURE 4. Stacked bar chart of percent leaf spray and under spray with percent over spray plotted by sensitivity and weed size for speed 1.

Percent Spray, Under Spray and Over Spray for Speed 1

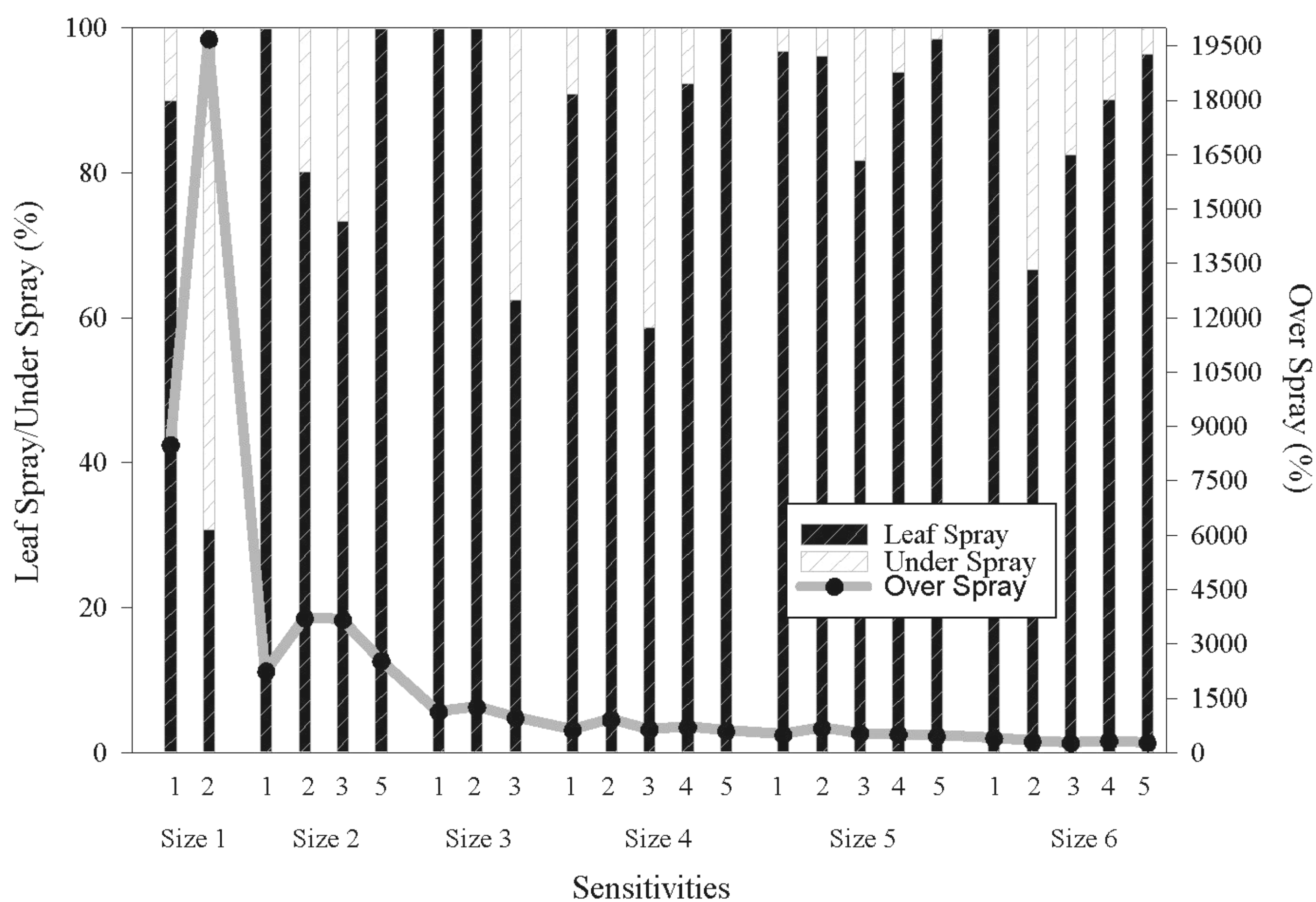


FIGURE LEGEND

FIGURE 5. Stacked bar chart of percent leaf spray and under spray with percent over spray plotted by sensitivity and weed size for speed 2.

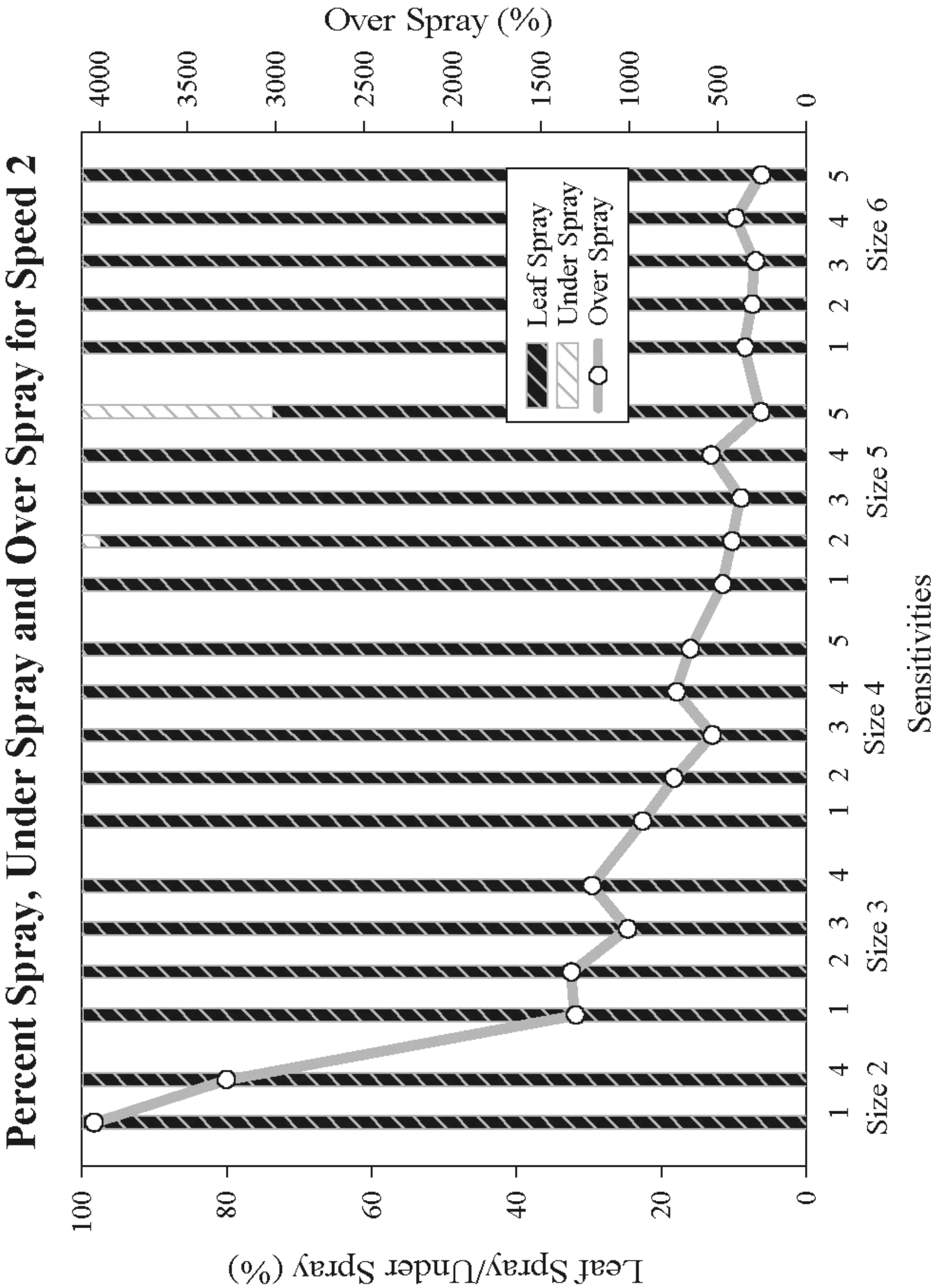

Percent Spray, Under Spray and Over Spray for Speed 2
Leaf Spray/Under Spray (%)
0
20
40
60
80
100
Over Spray (%)
0
500
1000
1500
2000
2500
3000
3500
4000
Leaf Spray
Under Spray
Over Spray
1 4
Size 2
1 2 3 4
Size 3
1 2 3 4 5
Size 4
1 2 3 4 5
Size 5
1 2 3 4 5
Size 6
Sensitivities

FIGURE LEGEND

FIGURE 6. Stacked bar chart of percent leaf spray and under spray with percent over spray plotted by sensitivity and weed size for speed 3.

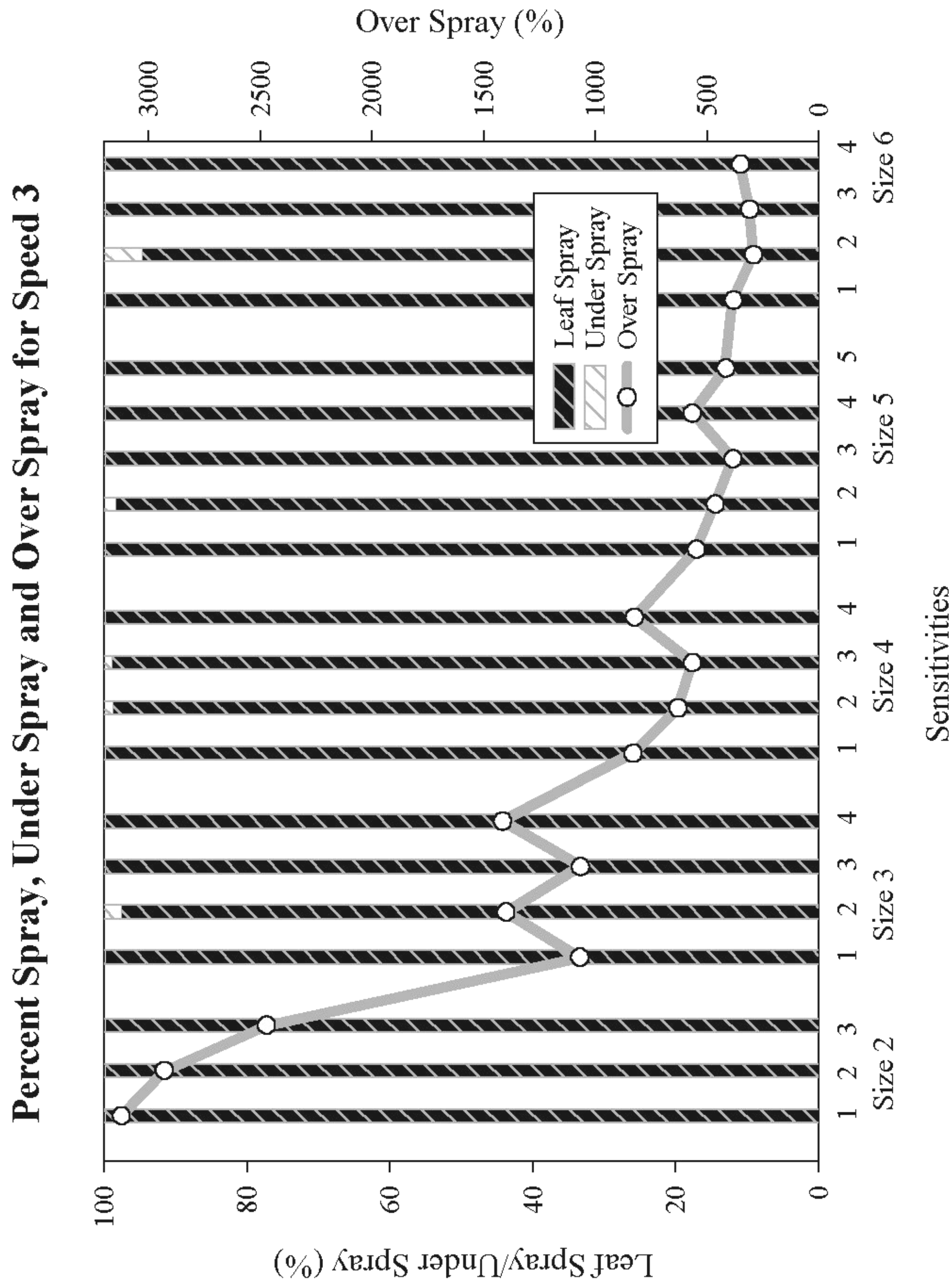
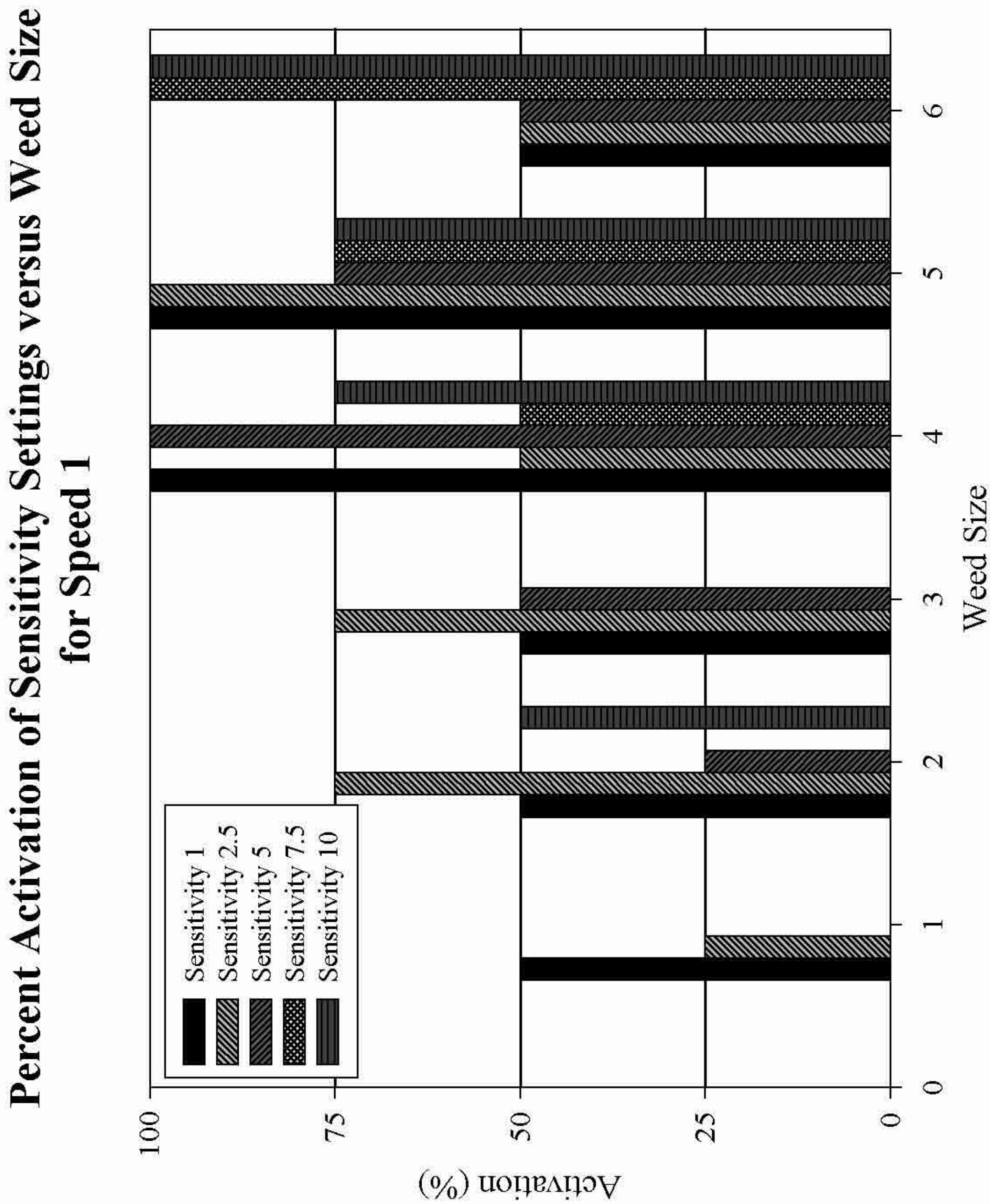

Percent Spray, Under Spray and Over Spray for Speed 3
Leaf Spray/Under Spray (%)
0
20
40
60
80
100
Over Spray (%)
0
500
1000
1500
2000
2500
3000
Sensitivities
1 2 3
Size 2
1 2 3 4
Size 3
1 2 3 4
Size 4
1 2 3 4 5
Size 5
1 2 3 4
Size 6
Leaf Spray
Under Spray
Over Spray

FIGURE LEGEND

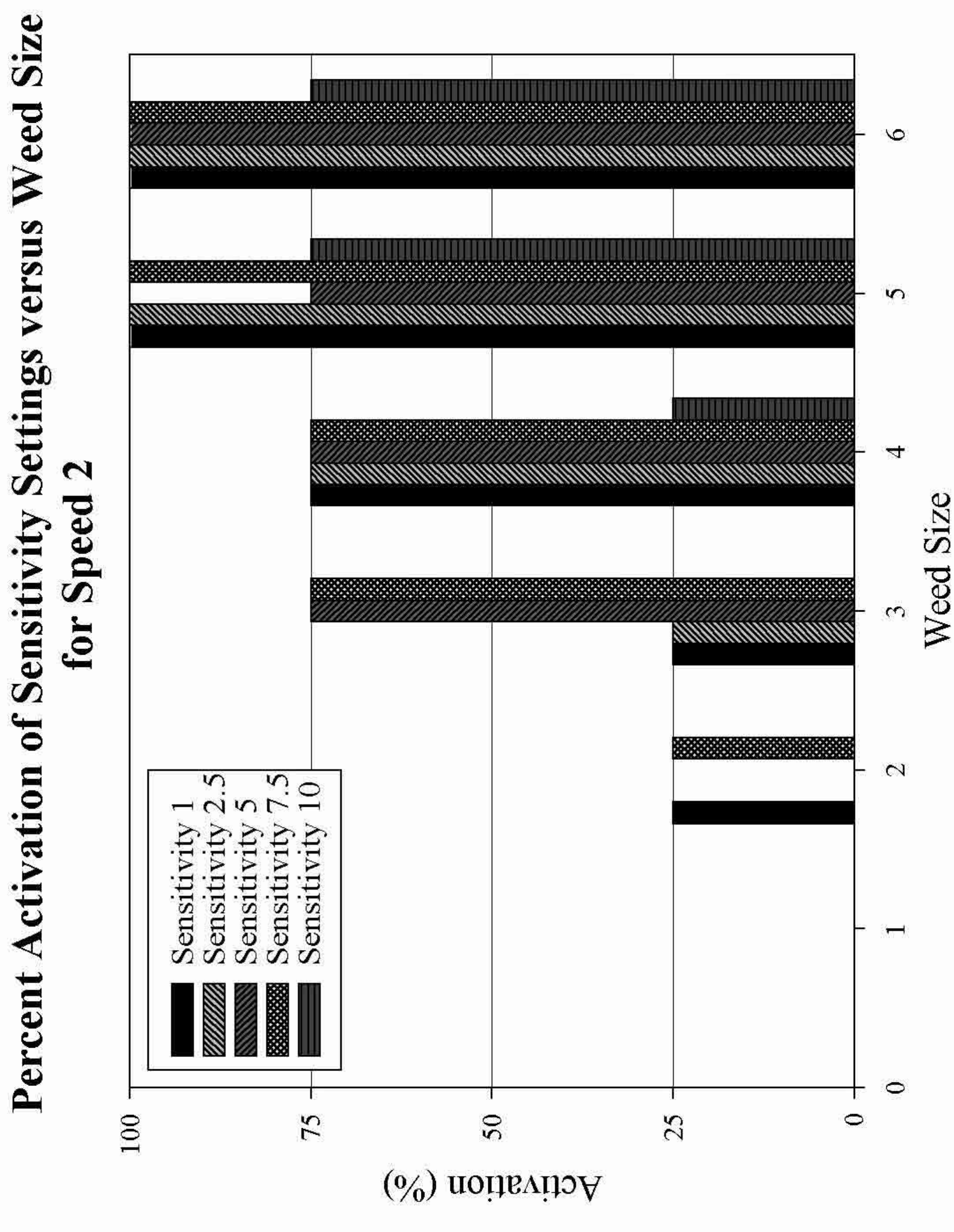
FIGURE 7. Percentage of activation of Patchen™ system for every sensitivity setting plotted by weed size for speed 1.



Percent Activation of Sensitivity Settings versus Weed Size for Speed 1
Activation (%)
100
75
50
25
0
Weed Size
0
1
2
3
4
5
6
Sensitivity 1
Sensitivity 2.5
Sensitivity 5
Sensitivity 7.5
Sensitivity 10

FIGURE LEGEND

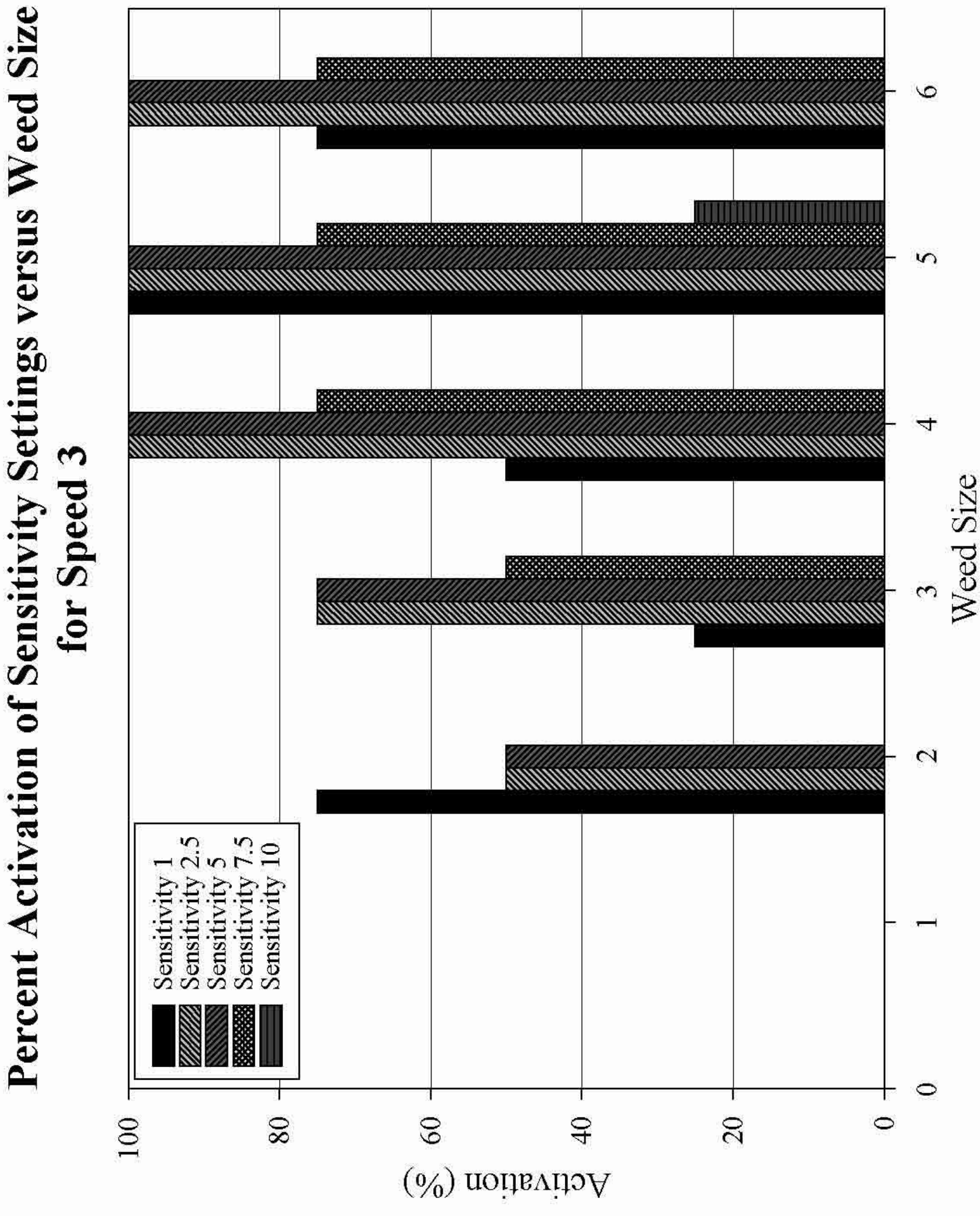
FIGURE 8. Percentage of activation of Patchen™ system for every sensitivity setting plotted by weed size for speed 2.



Percent Activation of Sensitivity Settings versus Weed Size
for Speed 2
Activation (%)
100
75
50
25
0
0
1
2
3
4
5
6
Weed Size
Sensitivity 1
Sensitivity 2.5
Sensitivity 5
Sensitivity 7.5
Sensitivity 10

FIGURE LEGEND

FIGURE 9. Percentage of activation of Patchen™ system for every sensitivity setting plotted by weed size for speed 3.

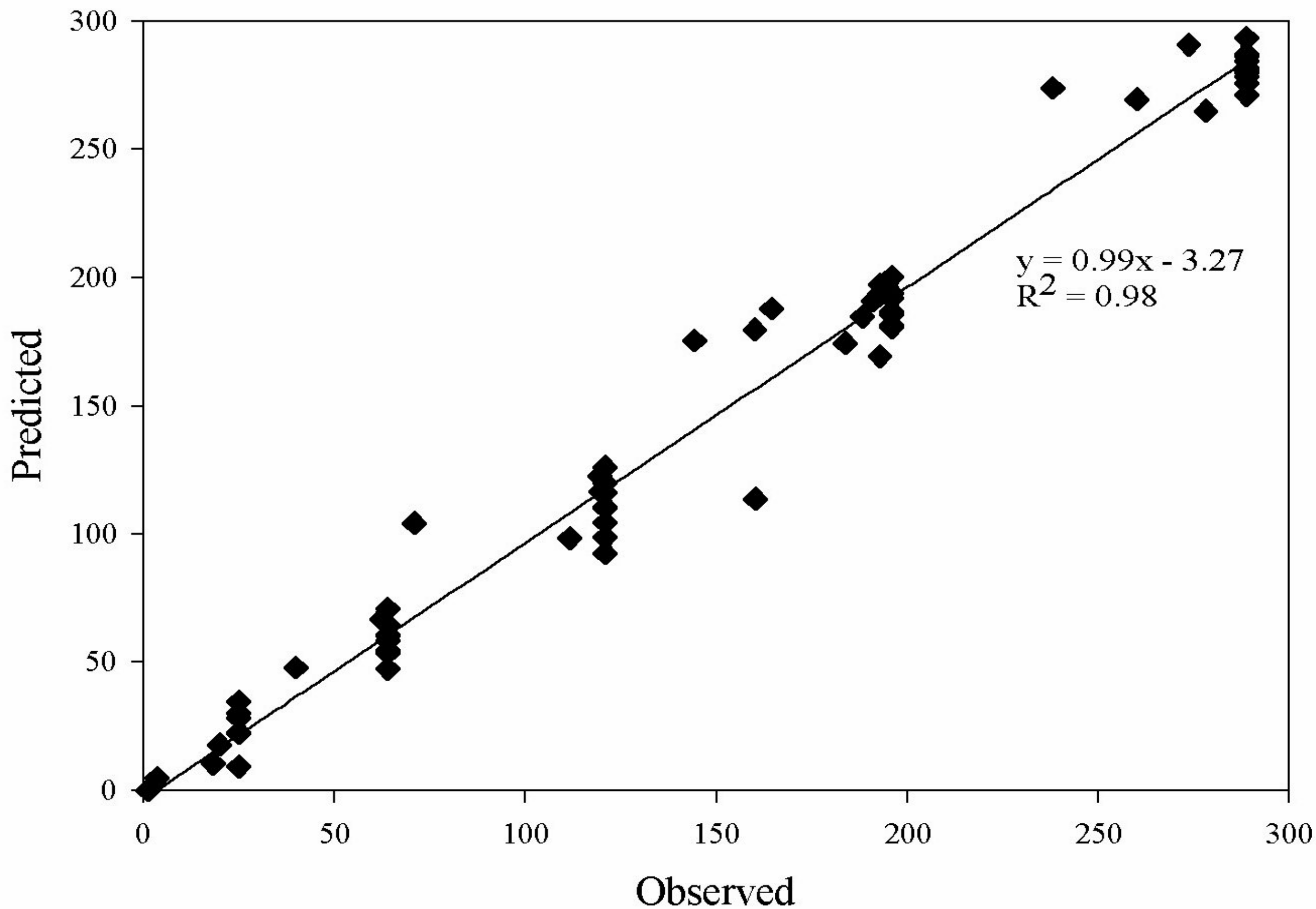


Percent Activation of Sensitivity Settings versus Weed Size for Speed 3
Activation (%)
0
20
40
60
80
100
Weed Size
0
1
2
3
4
5
6
Sensitivity 1
Sensitivity 2.5
Sensitivity 5
Sensitivity 7.5
Sensitivity 10

FIGURE LEGEND

FIGURE 10. Predicted values of leaf spray plotted against the observed values from a weed-activated sprayer.

Predicted Values for Leaf Spray versus Observed Values



SECTION V.
SUMMARY AND CONCLUSIONS

With the increasing need for pesticide use reduction, herbicide management is becoming more necessary. Utilizing the knowledge of weed spatial density can help in reducing the amount of herbicide applied, but obtaining this knowledge on a field scale has been very difficult in the past. Site-specific weed management (SSWM) could be the solution to this dilemma. These studies were conducted in order to develop a monitoring system for a weed-activated sprayer (WAS), to determine the proper calibration settings for the sprayer, and to use this monitoring system to map weed populations in an agricultural field.

As manufactured the WAS does not possess the ability to map weeds. This research developed several prototypes that allowed the machine to perform this task. Subsequent testing by comparing volume sprayed to volume predicted revealed design flaws and measurement errors in the first two prototypes. A final prototype was developed that combined electronic data logging of spray occurrences with location data from a global positioning system (GPS). Tests of this prototype helped determine the validity of the data collected with this monitoring system.

The new monitoring system was used to map weed populations in three fields. These measurements were compared to random measurements obtained by traditional human estimations and digital image analysis. Comparisons of human estimations and image analysis revealed good agreement in the data, while they were both very different from the data obtained with the WAS. This shows that although random human observations provide precise, accurate ground cover estimates in small areas, they do not provide accurate estimations over the entire field. Using the WAS to map weed populations provides an accurate determination of weed populations, and this knowledge can be used to make future weed control decisions.

In order to be able to use the WAS to map and/or control weeds in a field, it is important for the machine to be properly calibrated. Since the sensitivity setting determines if too much or too little herbicide is applied, a study was conducted to provide a calibration technique for the WAS. Several weed sizes were sprayed with a dye at different speeds and sensitivities. Digital analysis of the spray occurrences revealed the amount of plant material sprayed, the amount not sprayed, and the over spray. Models were developed that helped to minimize overspray and underspray while maximizing leaf spray. Other factors that affect the operation of the WAS are soil type and soil moisture content. In order to get the best performance, the machine should be calibrated on the darkest and wettest area of the field.